PETROLOGY AND GEOCHEMISTRY OF THE WILDCAT GULCH SYENITE, GUNNISON COUNTY, COLORADO

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ABSTRACT

Southwest of Gunnison, Colorado, within the Wildcat Gulch study area, syenitoid plutons intrude the Proterozoic Dubois Greenstone. Limited work has been done to document their lithologic character, ascertain their origin, or place them within the regional geology of central Colorado.

These syenitoid intrusions may be related to the igneous rocks of the ~1700 Ma Routt Plutonic Suite that formed during the Colorado orogeny that included episodes of arc collision and accretion during the Early Proterozoic. Alternatively, these syenitoid intrusions may be related to the rocks of the ~1400 Ma Berthoud Plutonic Suite that formed during the Berthoud orogeny in an episode of crustal thickening and shortening during the Middle Proterozoic. It is also possible that the syenitoid intrusions in the Wildcat Gulch study area are related to the syenite intrusions of the Iron Hill complex (570 Ma) that formed in an extensional continental environment.

This study provides a petrological and geochemical characterization and assessment of the informally named Wildcat Gulch syenite to aid the placement of these syenitoid intrusions within the regional geology of Colorado.

Through petrologic and geochemical analyses this study finds that the Wildcat Gulch syenite can be classified as quartz syenite and quartz monzonite. Although these rocks vary in terms of their mineralogy, they are geochemically very similar. The geochemical data suggest that the syenitoid varieties may have evolved from a single, possibly basaltic parent magma, through fractional crystallization. Additionally, it is suggested that the Wildcat Gulch syenite intrusions formed between 1390 - 1330 Ma as part of the Berthoud orogeny.

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DEDICATION

I would like to dedicate this thesis to my parents Mark and Sue Grosser, my brother Chris, my fiancée Aimee, and all my family and friends for their love and support.

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INTRODUCTION

In the Wildcat Gulch study area of Gunnison County, Colorado, several syenitoid plutons, informally referred to here as the Wildcat Gulch syenite, intrude the Early Proterozoic rocks of the Gunnison Uplift. The Gunnison Uplift, as described by Hedlund and Olson (1981), consists of Proterozoic rocks approximately bounded to the north by the Gunnison River, the Cimarron Fault to the south, and to the east by Cochetopa Creek. The syenitoid rocks in the Wildcat Gulch study area intrude the Dubois Greenstone of the Gunnison Uplift approximately 15 km south of the town of Gunnison, Colorado (Nelson and Riesmeyer, 1983) (Figure 1).

The syenitoid intrusions are variable in mineralogy, outcrop appearance, and mode of emplacement. Limited work had been done to document their lithologic and geochemical character, or place them within the regional geology of central Colorado.

Intrusive rocks such as the granite of Tolvar Peak, Powderhorn Granite, and the Iron Hill complex dominate the geology of the area (Figure 2; Table 1). The Wildcat Gulch syenite bodies may be related to these intrusions in formation timing and source material, or they may represent their own intrusive event.

The goal of this project is to define the spatial distribution and petrologic and geochemical variability of the Wildcat Gulch syenite. In addition, this study endeavors to constrain the intrusion of the Wildcat Gulch syenite into the geology of Colorado by reconnaissance mapping, sample collecting, petrographic and geochemical analyses, and by comparison with other research of the syenite intrusions and the regional geology of Colorado.

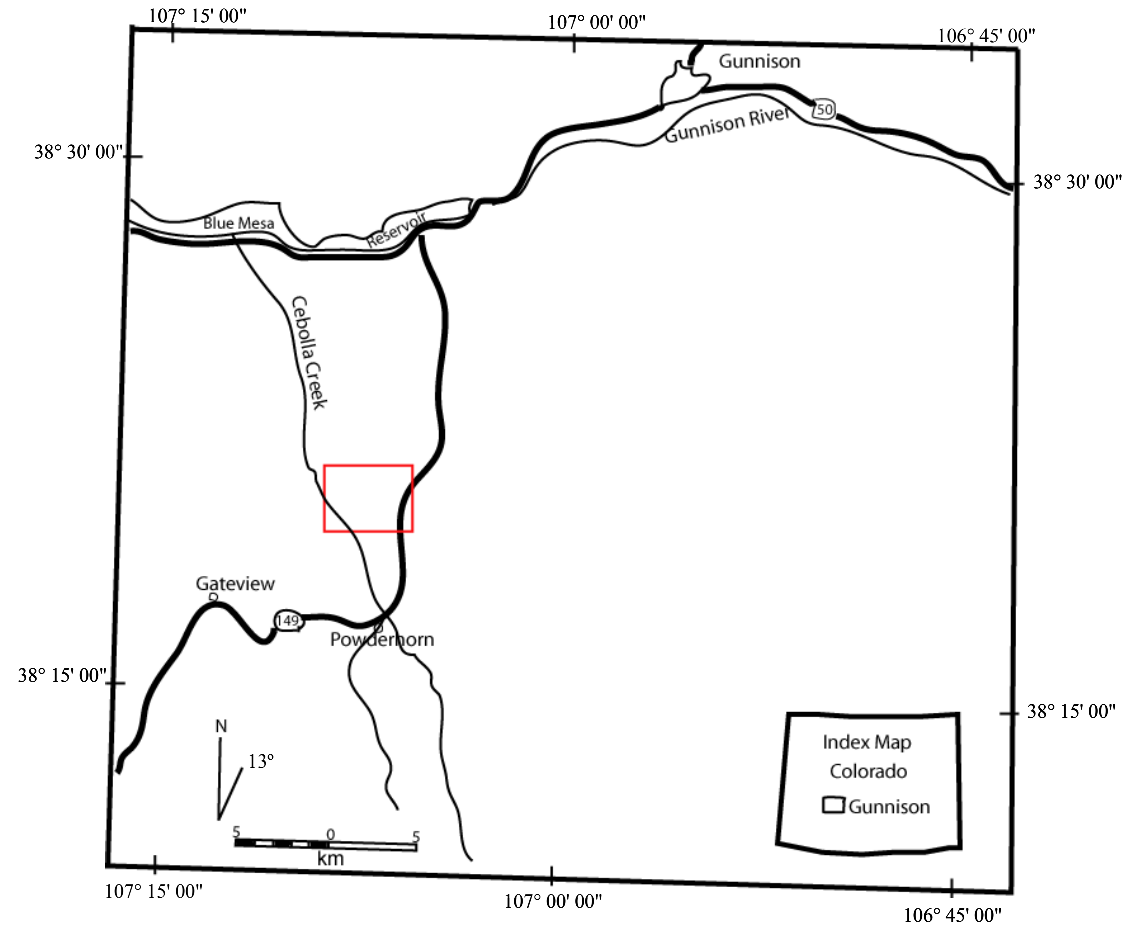


Figure 1. Geographic location of the Wildcat Gulch study area adapted from Condie and Nuter (1981). Study area outlined in red.

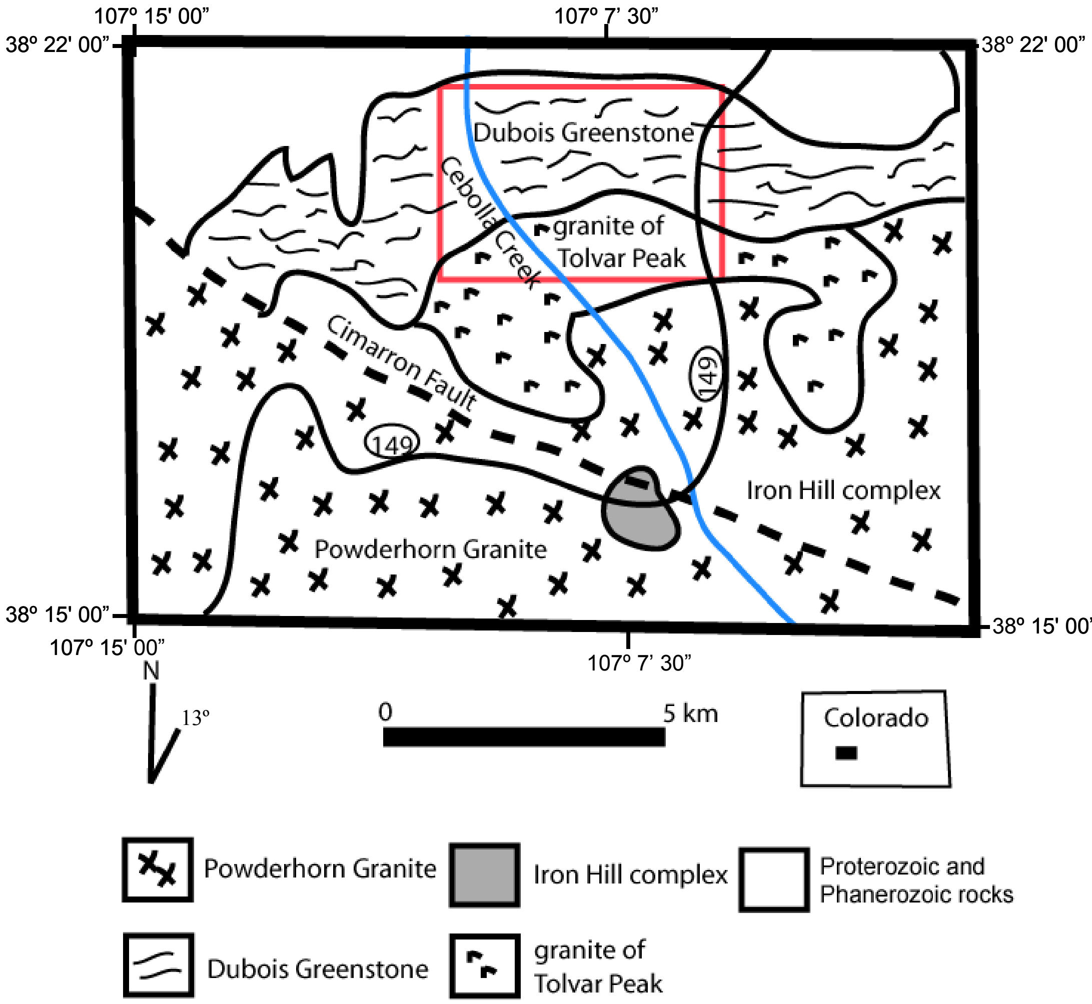


Figure 2. Location of the Wildcat Gulch study area within the context of the major geologic units of the area. Figure is modified from Hedlund and Olson (1981). Study area outlined in red.

Table 1. Summary of the igneous and metamorphic rocks/events in the Wildcat Gulch study area.

Igneous/Metamorphic Activity	Age in Ma	Characteristics	Selected References Cited
Sapinero Mesa Tuff	~34 - 24	Rhyolitic ash-flow tuff	Hedlund and Olson (1975)
Colorado Mineral Belt	~68	Proterozoic massive sulfide deposits, Tertiary veins and porphyries; continental setting	Tweto (1980c); Warner (1980)
Ordovician diabase dikes	510	Diabase; extensional continental setting	Olson et al. (1977)
Iron Hill complex	~570	Carbonatite,pyroxenite, uncompahgrite, ijolite, pyroxenite–syenite, and nepheline syenite; extensional continental setting	Olson et al. (1977);Armbrustmacher (1981); Armbrustmacher and Shannon (1987); Cappa (1988)
Pikes Peak batholith	1040	Granite, gabbro, and syenite; extensional continental setting	Tweto (1980a); Beane and Wobus (1999)
Syenite	1390 - 1330	Augite syenite, biotite syenite, melasyenite, hornblende syenite, quartz syenite and syenite, and biotite-calcite syenite dike	Olson and Hedlund (1973); Hedlund and Olson (1975); Olson et al. (1977)
Granite of Tolvar Peak	~1700	Granite; arc/subduction related	Tweto (1980a); Hedlund and Olson (1981); Nelson and Riesmeyer (1983)
Powderhorn Granite	~1700	Granite; arc/subduction related	Hedlund and Olson (1973, 1981); Tweto (1980a)
Dubois Greenstone	~1800 - 1700	Amphibolite, felsic schist, quartzite; back-arc Back-arc basin environment on continental crust Protoliths formed approximately 1800-1750 Ma; Metamorphosed approximately 1775 - 1700 Ma	Condie and Nuter (1981); Nelson and Riesmeyer (1983); Bickford and Boardman (1984); Tweto (1987); Hill and Bickford (2001); Sims and Stein (2003)

BACKGROUND

Regional Geology

The geologic history of Colorado is a complex series of events involving numerous episodes of igneous activity coupled with episodes of metamorphism, deformation, and sedimentation from the Proterozoic to the Cenozoic. Proterozoic rocks of Colorado are collectively referred to as the Colorado province, as well as the Transcontinental Proterozoic province (Sims and Stein, 2003; Figure 3; this study). These rocks form a belt of dominantly oceanic-affinity rocks that were accreted to the Archean Wyoming craton between ~1800 - 1700 Ma (Sims and Stein, 2003).

Precambrian (Proterozoic) rocks of Colorado were subdivided into six groups based upon stratigraphic age relationships by Tweto (1980b). These units, from oldest to youngest, are the ~1800 Ma biotitic gneiss, hornblendic gneiss, and felsic gneiss of the Proterozoic gneiss complex, the ~1700 Ma Routt Plutonic Suite, the ~1700 - 1400 Ma Uncompahgre Formation, the ~1400 Ma Berthoud Plutonic Suite, the ~1400 - 950 Ma Uinta Mountain Group, and the ~1000 Ma Pikes Peak Batholith (Tweto, 1980b).

Tweto (1987) states that for cartographic purposes the Precambrian eras were assigned a letter title and that the Proterozoic rocks were placed into these chronological based separations. These four eras were defined as Precambrian W (Late Archean), Precambrian X (Early Proterozoic), Precambrian Y (Middle Proterozoic), and Precambrian Z (Late Proterozoic) (Tweto, 1987). Precambrian W rocks are the oldest at ~3000 - 2500 Ma, and represent rocks not previously included in the original separation of Tweto (1980b). Rocks of the Precambrian W are not found within the Wildcat Gulch study area, and are not discussed in this study.

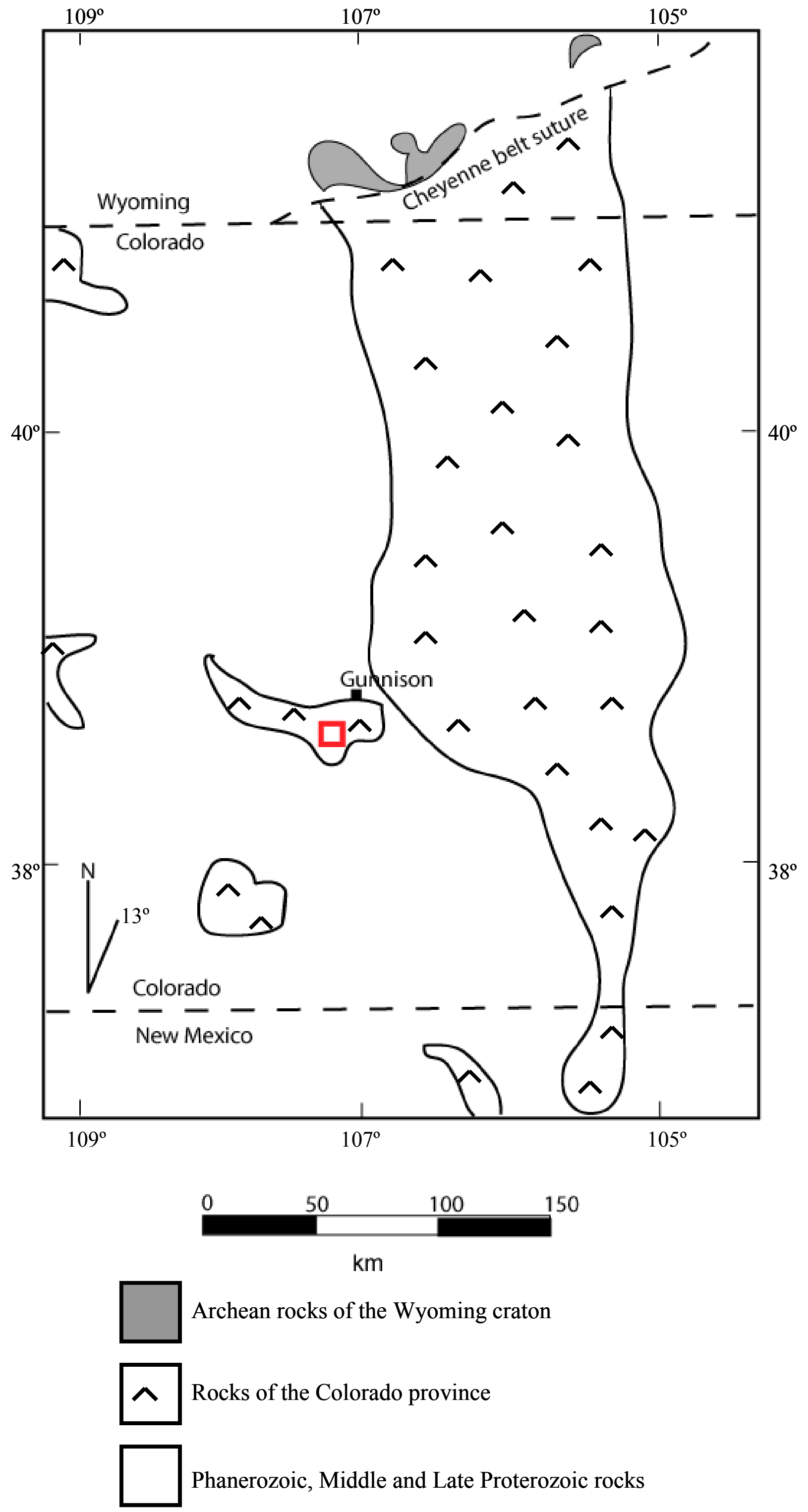


Figure 3. Generalized geologic map of rocks of the Colorado province modified from Sims and Stein (2003).

Precambrian X rocks at ~2500 - 1600 Ma include the Proterozoic gneiss complex and the Routt Plutonic Suite. Precambrian Y rocks range from ~1600 - 900 Ma and include the Berthoud Plutonic Suite, the Uinta Mountain Group (which does not crop out within the Wildcat Gulch study area), and the Pikes Peak Batholith. The ~1700 - 1400 Ma Uncompahgre Formation, which is not found within the Wildcat Gulch study area, falls within the Precambrian X and Precambrian Y time divisions (Tweto, 1987). Precambrian Z includes all rocks between ~900 - 570 Ma, and although the Iron Hill complex was not previously described by Tweto (1980b), it is included in the Precambrian Z time division by Tweto (1987).

In the following discussion of the regional geology of Colorado, the Precambrian (Proterozoic) rocks will be addressed by their X, Y, and Z time groupings with respect to the Wildcat Gulch study area. Because the literature on the tectonic environment of formation of many of the rocks within the Precambrian X and Y divisions is often contradictory, a discussion of the tectonic environment for these rocks will follow the discussion of the Precambrian X, Y, and Z time divisions.

Precambrian X

Within the Wildcat Gulch study area, Precambrian X rocks consist of metamorphosed rocks of the Proterozoic gneiss complex, and the intrusion of the Routt Plutonic Suite plutons.

The Proterozoic gneiss complex consist of both orthogneiss, which is the felsic and hornblendic gneiss of Tweto (1980b), and paragneiss, which is the biotitic gneiss of Tweto (1980b). No biotitic gneiss rocks exist in the study area. However, rocks of the felsic and hornblendic gneiss are present in the Wildcat Gulch study area. The felsic gneiss is thought to have a granitic or rhyolitic protolith, while the hornblende gneiss may have a basaltic or andesitic protolith (Tweto, 1987). These rocks may have formed in submarine continental-margin environment based on the presence of relict pillow lavas in the hornblendic gneiss (Tweto, 1987).

The Dubois Greenstone (Table 1) is an example of the felsic and hornblendic gneiss of Tweto (1987) that crops out in the study area. The Dubois Greenstone is a bimodal sequence of rocks composed of ultramafic schist, amphibolite, felsic schist, and metachert that have been metamorphosed from the upper greenschist to the amphibolite facies (Nelson and Riesmeyer, 1983). These rocks have a well-defined east to west lithologic strike, a near vertical foliation, and some localized isoclinal folding (Nelson and Riesmeyer, 1983). The majority of the rocks of the Dubois Greenstone are an amphibolite lithodeme that ranges from finely to coarsely crystalline. The finely-crystalline amphibolite often contains relict pillow lava structures. This relict evidence suggests that the protolith was deposited as subaqueous basalt flows while the more coarsely-crystalline amphibolite may represent gabbroic to diabasic protoliths (Nelson and Riesmeyer, 1983).

The other major lithodeme of the Dubois Greenstone is a felsic schist. These erosionally resistant rocks are thought to have either a felsic volcanic lava flow protolith or a pyroclastic debris protolith (Nelson and Riesmeyer, 1983). Tweto (1987) states that the protolith of the felsic schist formed approximately 1800 Ma based upon U-Pb zircon dates of 1765 +/- 5 Ma and 1740 +/- 5 Ma for metarhyolite of the Dubois Greenstone.

Additionally, the Dubois Greenstone contains discontinuous quartzite lenses that are oriented east-to-west parallel to the regional foliation. In the study area, they are concentrated near the mafic and felsic contacts (Nelson and Riesmeyer, 1983). These rocks are believed to have originated as seafloor chert deposits based upon their quartz dominated mineral assemblage, and their inter-bedded nature within the mafic and felsic lithodemes of the Dubois Greenstone (Nelson and Riesmeyer, 1983).

Condie and Nuter (1981) hypothesized that the protoliths of the Dubois Greenstone formed as a result of the melting of lower continental crust with an overall geologic setting of an immature back-arc basin, or a primitive island-arc setting based upon their geochemical and Sr isotopic data. Boardman and Condie (1986) later suggested a back-arc basin environment on continental crust for the protolith of these rocks.

Sims and Stein (2003), in their study of the evolution of the Colorado province, suggest that supracrustal rocks (e.g., Proterozoic gneiss complex of Tweto (1980b)) have oceanic arc origins. They present a two-arc model in which one arc is located near the Cheyenne belt suture, which is the boundary between the Archean craton and the arc-related rocks of Colorado (Figure 3). The other arc lies in the Gunnison area and includes rocks of the Dubois Greenstone (Sims and Stein, 2003). These two arcs are separated by 200 km of migmatitic biotite gneiss and schist (e.g., biotitic gneiss of Tweto (1987)), which is hypothesized to be back-arc basin fill or an accretionary prism (Sims and Stein, 2003).

The timing of formation and metamorphism of the Dubois Greenstone of the Proterozoic gneiss complex in many sources is based upon the ages of intrusions within the Dubois Greenstone, or upon the timing of the metamorphism of other rocks in the area. Condie and Nuter (1981) place the minimum age for the Dubois Greenstone at 1700 - 1650 Ma based on the U-Pb zircon dates of granite intrusions within the Dubois Greenstone. However, Bickford and Boardman (1984) state that the earliest of the bimodal volcanic rocks of the Dubois Greenstone erupted between 1770 - 1760 Ma based upon U-Pb zircon dates of granite bodies intruding the Dubois Greenstone.

Nelson and Riesmeyer (1983) place the timing of metamorphism of the Dubois Greenstone at 1800 - 1750 Ma based upon the work of Hedlund and Olson (1981). However, Hedlund and Olson (1981) state that the age of metamorphism is approximately 1800 - 1700 Ma based on the age of metamorphism of the Black Canyon Schist in the area at 1700 Ma by Rb-Sr techniques.

Later, Tweto (1987) states that the rocks of Proterozoic gneiss complex, including the Dubois Greenstone, were metamorphosed between 1775 - 1700 Ma based upon U-Pb zircon dates of metarhyolites. Additionally, Tweto (1987) states that the metamorphism of these rocks was due to the intrusion of plutons of the ~1700 Ma Routt Plutonic Suite. So, there is some inconsistency in defining the age of the formation and subsequent metamorphism of the Dubois Greenstone.

Based upon these arguments, the general consensus is that the protoliths of the Dubois Greenstone formed at approximately 1800 - 1750 Ma and that the metamorphism occurred between 1775 - 1700 Ma based upon the ages of other metamorphosed rocks in the area (Hedlund and Olson, 1981; Condie and Nuter, 1981; Nelson and Riesmeyer, 1983; Tweto, 1987).

Other Precambrian X rocks that crop out in the field area are the Powderhorn Granite and the granite of Tolvar Peak of the ~1700 Ga Routt Plutonic Suite. These batholiths and smaller intrusions range in composition from granite to gabbro and are foliated (Tweto, 1980b, 1987). Tweto (1987) suggests that the Routt Plutonic Suite rocks intruded the Proterozoic gneiss complex during and after the regional metamorphism, and are the cause of the metamorphism. If these intrusions are the cause of the metamorphism, then the intrusion of Routt Plutonic Suite plutons must have occurred as multiple events as an igneous intrusion cannot both cause the metamorphism and intrude after the metamorphism. This observation implies that some of the

Routt Plutonic Suite plutons caused the regional metamorphism through their intrusion, and that other plutons of the Routt Plutonic Suite intruded during and after the metamorphism. This hypothesis suggests that the intrusion of Routt Plutonic Suite plutons was a prolonged event with intrusions that caused the metamorphism and intrusions that followed the metamorphism. Alternatively, it is possible that the intrusions of the Routt Plutonic Suite plutons were not the cause of the regional metamorphism.

The granite of Tolvar Peak of the Routt Plutonic Suite is in contact with both the mafic and felsic lithodemes of the Dubois Greenstone (Figure 2). The highly foliated granite of Tolvar Peak was metamorphosed between 1750 - 1800 Ma, and is hypothesized to be coeval in formation with the basalt and rhyolite protoliths of the Dubois Greenstone (Hedlund and Olson, 1981; Nelson and Riesmeyer, 1983).

The Powderhorn Granite of the Routt Plutonic Suite is located south and west of Wildcat Gulch (Figure 2). It is also reported to be foliated, and is hypothesized to be coeval with the granite of Tolvar Peak and Dubois Greenstone according to Hedlund and Olson (1973, 1981).

However, Tweto (1987) does not state that these rocks are coeval with the Dubois Greenstone. If these rocks intrude and caused the metamorphism of the Dubois Greenstone, then it is unlikely that the granite of the Tolvar Peak and the Powderhorn Granite are coeval with the protoliths of the Dubois Greenstone.

Additionally, Bickford and Boardman (1984) used U-Pb techniques on zircon to date the granite of the Tolvar Peak at 1757 +/- 10 Ma and the Powderhorn Granite at 1751 +/- 6 Ma. These overlapping age determinations would place the intrusions of these bodies at the end of the 1800 - 1750 Ma timing of metamorphism of Hedlund and Olson (1981) and Nelson and Riesmeyer (1983). This observation implies that these granite intrusions are not coeval with the protoliths of the Dubois Greenstone. However, if these intrusions are coeval with the protoliths of the Dubois Greenstone, and are metamorphosed to the same degree as the Dubois Greenstone, then it is more likely that the timing of metamorphism at 1775 - 1700 Ma of Tweto (1987) is a more viable hypothesis.

Precambrian Y

Precambrian Y rocks consist of the ~1400 Ma igneous rocks of the Berthoud Plutonic Suite and the ~1000 Ma Pikes Peak Batholith (Tweto, 1987). The rocks of the Berthoud Plutonic Suite (1480 - 1350 Ma) are anorogenic, nonfoliated batholiths and smaller plutons mostly located in the southern half of Colorado (Tweto, 1987).

Compositionally, most rocks of the Berthoud Plutonic Suite are granite, quartz monzonite, and syenite (Tweto, 1987). Syenite varieties mapped and later included into the Berthoud Plutonic Suite consist of augite syenite, biotite leucosyenite, hornblende and biotite melasyenite, shonkinite, and minette (Hunter, 1925; Olson and Hedlund, 1973; Hedlund and Olson, 1975; Tweto, 1987).

Olson et al. (1977) analyzed several syenite intrusions of the Precambrian Y. They reported K-Ar biotite mineral separate dates on three syenite samples and a biotite-calcite syenite dike at 1390 - 1330 Ma, which is coincident with the Berthoud Plutonic Suite (Table 1).

The last unit of Precambrian Y rocks is the ~1000 Ma Pikes Peak Batholith that is located in the southern Front Range approximately 160 km northwest of the Wildcat Gulch study area (Tweto, 1980b; Table 1; this study). The Pikes Peak Batholith is primarily granite with subordinate syenite and gabbro (Tweto, 1980b). The batholith is nonfoliated having high total alkalis, low CaO, and high FeO to MgO ratio suggesting that the bodies are anorogenic (Tweto, 1980b; Beane and Wobus, 1999).

Beane and Wobus (1999) studied the Sugarloaf Syenite of the Pikes Peak Batholith. They suggest that, because the syenite intrusions are located near faults, it is possible that the magma may have risen along these fault lines in an extensional environment (Beane and Wobus, 1999). They further interpret these syenite bodies to have evolved through fractional crystallization of a mafic mantle source, possibly basalt in an extensional continental environment (Beane and Wobus, 1999).

Precambrian Z

Thirteen km to the south of the study area, Precambrian Z rocks consist of the ~570 Ma Iron Hill complex (Figure 2; Table 1). The Iron Hill complex is located south of the Cimarron Fault and to the south of the Wildcat Gulch study area (Figure 2). The Iron Hill complex is a zoned carbonatite surrounded by pyroxenite, uncompahgrite, ijolite, and a fenitized zone of pyroxenite–syenite and nepheline syenite (Armbrustmacher, 1981). In addition, carbonatite and trachyte dikes related to the Iron Hill complex crosscut the Dubois Greenstone in the study area (Nelson and Riesmeyer, 1983).

Radiometric age determinations of the date of intrusion of the Iron Hill complex has resulted in several interpretations. Olson et al. (1977) used Rb-Sr methods on mica separates, as well as whole rock samples from a pyroxenite-syenite, and obtained a date of 579+/-10 Ma. They also extracted zircon from the nepheline syenite that produced dates of 525 Ma and 583 Ma (Olson et al., 1977). Armbrustmacher (1981) estimated ages for these intrusions at 570 Ma and older. For the purpose of further discussion in this study, the age of the Iron Hill complex is referred to as ~570 Ma.

Olson et al. (1977) states that the Iron Hill complex in an extensional continental environment based on Sr isotopic data and the presence of deep fracture zones in the area. Armbrustmacher and Shannon (1987) hypothesized that the formation of the Iron Hill complex occurred by the assimilation of marble, the metasomatism of pyroxenite, or by means of immiscible fluids. Another hypothesis suggests that the carbonatite formed from an alkalic magma generated in the upper mantle based upon Rb/Sr and Sm/Nd data (Armbrustmacher and Shannon, 1987).

Tectonic Synthesis for the Proterozoic Rocks

Early studies of the geology of Colorado attribute much of the volcanism, plutonism, and metamorphism in the Proterozoic to periods of arc collision and accretion representing southward growth of Laurentia (Tweto 1980a, 1980b).

Later research by Van Schmus et al. (1993) and Hill and Bickford (2001) suggest that the Precambrian rocks, which were originally thought to represent periods of arc accretion, are actually a suite of bimodal rocks formed in a continental extensional setting. They suggest that the rocks of the Trans-Hudson-Penokean (THP) orogens to the north in Wyoming (1900 - 1800 Ma) are also located farther south into Colorado and Arizona (Hill and Bickford, 2001).

Sims and Stein (2003) attribute growth of Laurentia to the accretions of arc and oceanic rocks between 1800 - 1650 Ma, of which the initial collision occurred along the Cheyenne belt suture in Wyoming between 1780 - 1750 Ma (Sims and Stein, 2003; Figure 3, this study). This hypothesis is similar to early researchers hypotheses on the continental growth of Laurentia (Tweto 1980a, 1980b).

Based on their hypothesis of periods of arc collision and accretion during the Proterozoic, Sims and Stein (2003) define two new orogenic events in Colorado: the Colorado orogeny and the Berthoud orogeny. The Colorado orogeny includes the events that involved the accretion of arc and ocean related rocks to the Archean Wyoming craton between 1800 - 1700 Ma (Sims and Stein, 2003). This time frame includes the formation of the rocks of the Proterozoic gneiss complex and the Routt Plutonic Suite of Tweto (1987). The Berthoud orogeny involves ductile shearing and folding during 1450 - 1350 Ma in an intra-continental setting (Sims and Stein, 2003). This event corresponds to the intrusion of the ~1400 Ma Berthoud Plutonic Suite of Tweto (1987).

Sims and Stein (2003) suggest that the Colorado orogeny formed the tectonic outline of the Colorado province, and that subsequent tectonic events are superimposed, or partially controlled, by this framework. Shear zones and faults created in this orogeny became reactivated during the ~1400 Ma Berthoud orogeny, and channeled later plutonic activity that included the formation of the Colorado mineral belt (Sims and Stein, 2003).

The Colorado orogeny consisted of deformation, metamorphism and plutonism between 1800 - 1650 Ma with the accretion of arc related rocks to the Wyoming craton (Sims and Stein, 2003). Plutonic rocks of this event consist of subduction related, calc-alkaline granitoids that represent continued convergence along the Cheyenne belt (Sims and Stein, 2003).

The deformation associated with this event affected not only the rocks of the Wyoming craton, but the arc rocks as well, subjecting them to greenschist and amphibolite facies metamorphism (Sims and Stein, 2003). Because Sims and Stein (2003) do not define the timing of metamorphism, it is assumed that it is approximately 1775 - 1700 Ma as stated by Tweto (1987).

The presence of 1720 Ma rocks in New Mexico suggest that accreted rocks of the Colorado province formed a belt that was over 1000 km wide (Sims and Stein, 2003). In addition, the knowledge that Proterozoic rocks in Colorado become younger to the south suggests that there were several episodes of accretion during the Colorado orogeny (Sims and Stein, 2003).

The Berthoud orogeny from 1450 - 1350 Ma consisted of intraplate plutonism in a continental setting with ductile shear zones up to 5 km wide and folding of the rocks of the Colorado province (Sims and Stein, 2003). These shear zones are common in the Colorado mineral belt (Sims and Stein, 2003).

Coeval with the shearing was the emplacement of granitoid plutons and metamorphism (Sims and Stein, 2003). These intrusions represent both crustal shortening and crustal thickening by the intrusions of granitoid plutons (Sims and Stein, 2003). These plutons are considered "anorogenic," or A-type, granitoids with high potassium and iron contents (Sims and Stein, 2003). Sims and Stein (2003) state that the term "anorogenic" implies that these rocks formed after a known orogenic event. However, they state that structural studies suggest that some of the granite intrusions formed in a crustal shortening event (Sims and Stein, 2003). This hypothesis suggests that some of the plutons associated with the Berthoud orogeny are "orogenic" while other plutons may have formed after this orogenic event and are considered "anorogenic."

These plutons are hypothesized to have formed in a transpressional-transtensional environment along ductile shear zones (Sims and Stein, 2003). They suggest that these plutonic rocks of the Berthoud orogeny formed through a combination of crustal and basaltic melting, and were emplaced along shear zones (Sims and Stein, 2003).

While the Colorado orogeny and the Berthoud orogeny are not technically orogenies in that they may not be considered mountain building events, the term orogeny is used in this study when referring to these events of Sims and Stein (2003).

Paleozoic

Within the Wildcat Gulch study area, the only Paleozoic rocks that exist are crosscutting Ordovician diabase dikes (Olson et al., 1977). Within the study area, there are approximately 40 diabase dikes that have a general northwest trend (Olson et al., 1977). These dikes are hypothesized by Olson et al. (1977) to have formed in an extensional, continental setting.

Mesozoic

The Mesozoic record within the Wildcat Gulch study area consists of rocks and mineralization associated with the Laramide orogeny and the formation of the Colorado mineral belt (Figure 1). The Colorado mineral belt has been the center of Au and Cu mineralization in Colorado (Romberger, 1980). Common mineralization found in the Colorado mineral belt include sphalerite, molybdenite, pyrite, chalcopyrite, and galena, as well as native gold, silver, and uraninite (Romberger, 1980).

The economic mineralization is thought to have formed by the injection of numerous porphyries and other intrusions that formed during and after the 65 Ma Laramide orogeny (Warner, 1980; Tweto 1980c). This zone also houses Proterozoic massive sulfide deposits of the Gunnison gold belt, early-to-mid-Tertiary veins in Precambrian-aged rock, veins and replacement deposits in sedimentary rocks, disseminated and stockwork Mo mineralization in mid-Tertiary porphyries, and precious and base-metal veins in volcanic rock (Romberger, 1980).

Shear zones and faults created in the Colorado orogeny were hypothesized by Sims and Stein (2003) to have acted as channels for the plutonic activity associated with the formation of the Colorado mineral belt (Sims and Stein, 2003).

Cenozoic

Within the Wildcat Gulch study area, Cenozoic rocks consist of Tertiary volcanic rocks. Within the field area, these volcanic rocks consist of the Sapinero Mesa Tuff (Hedlund and Olson, 1975). This San Juan equivalent, Oligocene-aged rhyolitic ash-flow tuff is found in the northern portion of the Wildcat Gulch study area where it unconformably overlies Proterozoic rocks of the Dubois Greenstone and an augite syenite outcrop (Hedlund and Olson, 1975).

Summary

The geology of the Wildcat Gulch study area consists of metamorphic rocks of the Proterozoic gneiss complex, intrusive rocks of the Routt Plutonic Suite, Berthoud Plutonic Suite, and Iron Hill complex, the intrusion of Ordovician diabase dikes, and the Cenozoic volcanic rocks of the Sapinero Mesa Tuff (Table 1).

Tectonically the formation of Colorado is hypothesized to have been the result of episodes of arc collision and accretion in the Proterozoic defined as the Colorado orogeny by Sims and Stein (2003). The Berthoud orogeny of Sims and Stein (2003) followed this event of arc accretion. The Berthoud orogeny consisted of intraplate plutonism associated with ductile shearing. Intrusions of this orogeny represent crustal shortening and thickening in a transpressional-transtensional environment (Sims and Stein, 2003). After the Berthoud orogeny, the Pikes Peak Batholith, Iron Hill complex, and the Ordovician diabase dikes, are hypothesized to have formed in an extensional continental environment (Olson et al., 1977; Beane and Wobus, 1999).

Previous Investigations

Previous investigations into the syenitoid rocks of the Wildcat Gulch study area are limited to reconnaissance and economic resource mapping, minimal petrographic and geochemical analysis, and four radiometric age determinations (Hunter, 1925; Olson and Hedlund, 1973; Hedlund and Olson, 1975, 1981; Olson et al., 1977).

Hunter (1925), in his study of Precambrian rocks of the Gunnison area, mapped syenite occurrences in the Wildcat Gulch study area. He also sampled and petrographically analyzed an augite syenite from within Wildcat Gulch and a biotite syenite from Lot mine to the south of the study area. Hunter (1925) describes the augite syenite as a dark colored, fine-grained rock containing abundant microcline, augite, and biotite with lesser amounts of amphibole, apatite, quartz, and rutile. The biotite syenite is described as being similar to the augite syenite except that the biotite syenite is greatly enriched in biotite and contains only minor augite (Hunter, 1925). In addition, Hunter (1925) reports a major element oxide analysis of the augite syenite from the Wildcat Gulch study area.

Olson and Hedlund (1973) and Hedlund and Olson (1975) mapped the Wildcat Gulch area in detail in their reconnaissance survey for Th resources in the 7 ½-minute Gateview and Powderhorn quadrangles in central Colorado. In addition, Olson and Hedlund (1973) and Hedlund and Olson (1975) defined five varieties of syenite found in their mapping as augite syenite, biotite syenite, quartz syenite and syenite, nepheline syenite, and pyroxenite-nepheline syenite in the area. Hedlund and Olson (1975) describe the augite syenite as a gray, fine-grained rock containing augite, microcline, hornblende, actinolite, chlorite, biotite, with accessory quartz, iron, apatite, and calcite. The biotite syenite is a gray, medium-grained syenite containing microcline, biotite, sodic amphibole, quartz, with accessory augite, calcite, albite, chlorite, and epidote (Hedlund and Olson, 1975). The quartz syenite and syenite of Hedlund and Olson (1975) is described as a light pink rock containing microcline, biotite, and quartz, with accessory hornblende and apatite.

The nepheline syenite and the pyroxenite-nepheline syenite mapped by Hedlund and Olson (1975) is from the ~570 Ma Iron Hill complex. These syenite intrusions are described as a light gray nepheline syenite, which intrudes the pyroxenite-nepheline syenite variety (Hedlund and Olson, 1975). Due to mine reclamation and environmental remediation, samples of these intrusions could not be taken for comparison with this study.

Olson et al. (1977) analyzed several syenite intrusions in the Precambrian X and Y in the area. They report K-Ar biotite mineral separate dates on three syenite samples at 1390 - 1380 +/- 40 Ma and a biotite-calcite syenite dike at 1330 +/- 36 Ma in the Wildcat Gulch study area (Olson et al., 1977). The three syenite samples, which are located within the Wildcat Gulch study area, consist of an augite syenite, biotite syenite, and quartz syenite and syenite as mapped by Hedlund and Olson (1975).

Based upon the K-Ar dates of Olson et al. (1977) and their previous mapping in the area, Hedlund and Olson (1981) define a period of alkalic intrusion that occurred between 1390 - 1330 Ma with the emplacement of approximately 20 syenite intrusions of varying lithologies in the Wildcat Gulch study area. These syenite intrusions consist of biotite syenite, augite syenite, and leucosyenite (Olson and Hedlund, 1973; Hedlund and Olson, 1975, 1981). In their study, Hedlund and Olson (1981) report on the major oxide concentrations of three syenite samples, one Powderhorn Granite sample, and one granite of Tolvar Peak sample. Because no sample locations are given in the Hedlund and Olson (1981) study it is assumed that the three syenite samples correspond to the K-Ar dated syenite samples of the Olson et al. (1977) study based upon their previous record of prior research on syenite intrusions in the area.

Nelson and Riesmeyer (1983) described carbonatite and trachyte dikes found within the study area that are related to the Iron Hill complex. Nelson and Riesmeyer (1983) describe the trachyte as red in color and containing dominantly K-feldspar. This matches the description of the trachyte at the entrance to Wildcat Gulch on Highway 149 according to the work of Hedlund and Olson (1975). Nelson and Riesmeyer (1983) describe the carbonatite as a light gray rock containing biotite and calcite.

Statement of the Problem

Fieldwork during 2002 and 2003 found that syenitoid intrusions of the Wildcat Gulch study area were not deformed, and showed a variety of intrusive contact relationships from irregular to blocky assimilation contacts with the mafic lithodeme of the Dubois Greenstone. In the study area, the Dubois Greenstone has been metamorphosed to upper greenschist to amphibolite facies, and is highly deformed (Nelson and Riesmeyer, 1983). The lack of deformation of the syenite suggests that their emplacement is potentially younger than the Dubois Greenstone, as suggested by Olson et al. (1977).

This study evaluates three hypotheses for the origins of these syenite intrusions. The first hypothesis is that they may be genetically associated with the formation of the granite of

Tolvar Peak and/or the Powderhorn Granite of the ~1700 Ma Routt Plutonic Suite and Colorado orogeny (Hedlund and Olson, 1981; Nelson and Riesmeyer, 1983; Sims and Stein, 2003). However, because the Wildcat Gulch syenite intrusions show no signs of deformation in either hand sample or thin section during preliminary analyses, this observation is contrary to the documented foliation within the granite of Tolvar Peak and Powderhorn Granite (Olson and Hedlund, 1973; Hedlund and Olson, 1975; Nelson and Riesmeyer, 1983). A portion of this study will address whether the Powderhorn Granite and granite of Tolvar Peak are deformed so as to evaluate this hypothesis.

The second hypothesis is that the Wildcat Gulch syenite intrusions may be related to the syenite intrusions of Olson et al. (1977) and Hedlund and Olson (1981). The age determinations of Olson et al. (1977) would place the Wildcat Gulch syenite within the ~1400 Ma Berthoud Plutonic Suite of Tweto (1987) and the Berthoud orogeny of Sims and Stein (2003).

The third hypothesis is the Wildcat Gulch syenite may be related to the formation of the ~570 Ma Iron Hill complex that formed after the Berthoud orogeny (Armbrustmacher, 1981; Sims and Stein, 2003). Because the Iron Hill complex has limited access due to environmental restoration activities, direct sampling was not possible, and comparisons are based upon data of Armbrustmacher (1981) and Cappa (1998). The syenite intrusive rocks of the Iron Hill complex contain nepheline, and if the Wildcat Gulch syenite is related, they should also contain nepheline (Armbrustmacher, 1981; Cappa, 1998). The presence of a feldspathoid in the Wildcat Gulch syenite samples would suggest the possibility of an Iron Hill complex origin. However, if no feldspathoids minerals are found within the Wildcat Gulch rocks, it may only suggest that the petrographic descriptions of the Iron Hill complex samples were incompletely surveyed.

If the Wildcat Gulch syenite intrusions are not related to either of these intrusions, then it is possible that they define their own intrusive event.

In order to evaluate the hypotheses for the origin of the Wildcat Gulch syenite, it was necessary to collect representative samples of both the Wildcat Gulch syenite and the surrounding country rocks. Additionally, sampling and outcrop level analysis of the Wildcat Gulch syenite and the surrounding country rocks provides relative age control to these rocks.

Petrographic analyses aids in the evaluation as to how many syenitoid varieties are present within the area, as well as to determine any petrographic correlations that the syenitoid intrusions may have with the surrounding country rocks including the Powderhorn Granite and granite of Tolvar Peak.

Geochemical characterization of the Wildcat Gulch syenite and the country rocks of the area may further aid in the determination of how many syenitoid varieties are present, as well as determine any correlations between the Wildcat Gulch syenite and the surrounding country rocks in the study area.

Study Area

The Wildcat Gulch study area is located in Gunnison County, Colorado southwest of the town of Gunnison, Colorado (Figure1). Wildcat Gulch is located north of the Cimarron Fault, the granite of Tolvar Peak, and Iron Hill complex (Figure 2). Wildcat Gulch is located off of Highway 149 at the top of Nine Mile Hill, south of Blue Mesa Reservoir. The study area is within the Gunnison Uplift, which is bounded in the north by the Gunnison River and in the south by the Cimarron Fault (Hedlund and Olson, 1981; Figure 2; this study). The study area is also located within the northeast-trending Colorado mineral belt.

The Wildcat Gulch study area was chosen for several reasons. This area contains numerous outcrops of syenitoid of several different varieties, three of which were sampled and dated in the study of Olson et al. (1977). Additionally, this area has been previously mapped by Hunter (1925), Olson and Hedlund (1973), and Hedlund and Olson (1975), as well as been studied as part of the Th resources regional study of Olson et al. (1977). Wildcat Gulch is in close geographic proximity to the Powderhorn Granite and granite of Tolvar Peak, which are two potential intrusions that may be related to the Wildcat Gulch syenite. Additionally, the mining activity in this area has created numerous unimproved roads that allow for easy access to the field area.

Field and Laboratory Procedures

Mapping of the Wildcat Gulch syenite and their contacts was completed at the reconnaissance level for this project based upon the Olson and Hedlund (1973) and Hedlund and Olson (1975) geologic maps. The contact relationships, where visible, between the syenite intrusions and their wall rocks were examined with respect to the Olson and Hedlund (1973) and Hedlund and Olson (1975) geologic maps. Sample collection including the Dubois Greenstone, Powderhorn Granite, granite of Tolvar Peak, as well as the Wildcat Gulch syenite occurred during the summer of 2003. Figure 4 and Table 2 illustrate the location of petrologic and geochemical samples. Sampling and petrographic thin section preparation will be discussed in the PETROLOGY chapter. Geochemical procedures and techniques of analysis will be discussed in the GEOCHEMISTRY chapter.

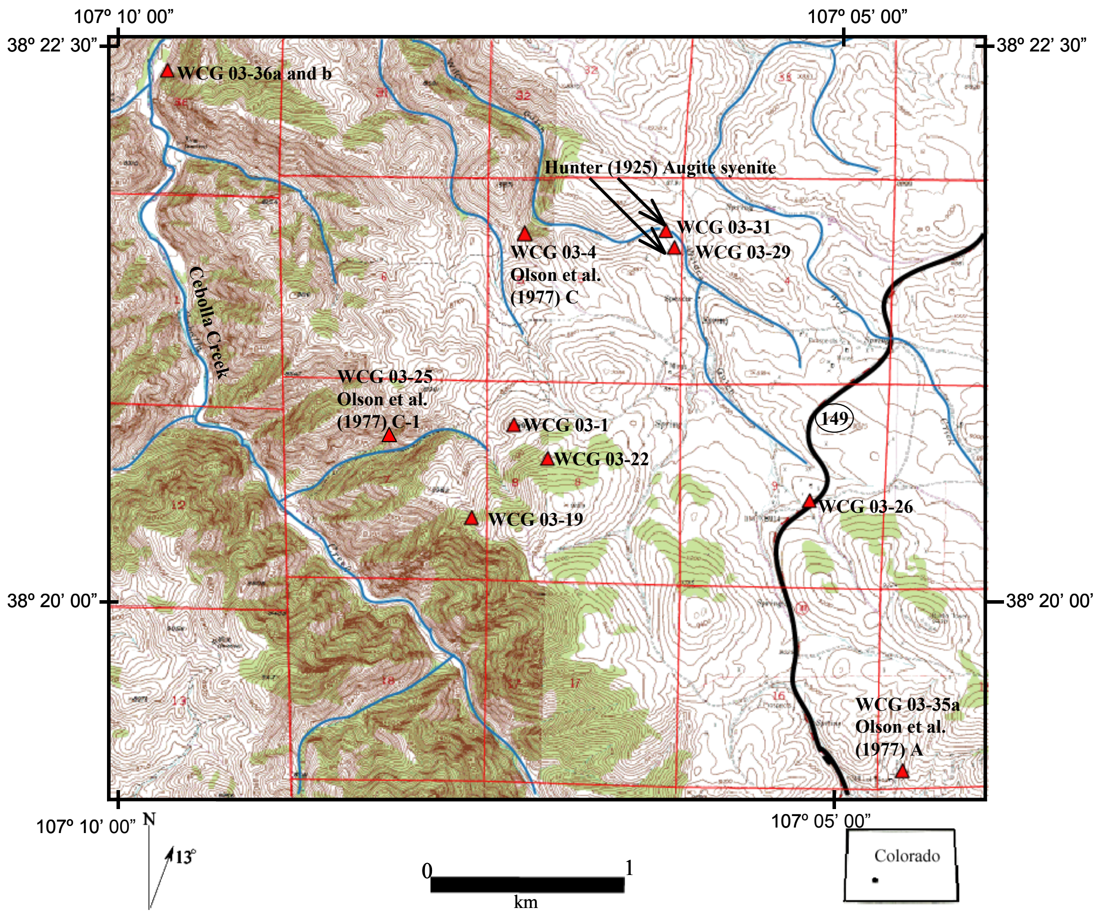


Figure 4. Location map of the Wildcat Gulch petrologic and geochemical samples, including the sample locations of Olson et al. (1977). Only samples with detailed petrographic and geochemical analyses are shown. Figure is adapted from the Powderhorn and Gateview 7.5 minute topographic map (USGS, 1982a, 1982b)

Table 2. Latitude and longitude locations for the geochemical samples of the Wildcat Gulch study area.

Sample	Latitude	Longitude
WCG03-01	38° 20' 45"	107° 07' 44"
DUP-WCG03-01	38° 20' 45"	107° 07' 44"
WCG03-04	38° 21' 32"	107° 07' 39"
WCG03-29A	38° 21' 30"	107° 06' 54"
WCG03-31	38° 21' 34"	107° 06' 57"
WCG03-35A	38° 19' 19"	107° 05' 36"
WCG03-36B	38° 22' 27"	107° 09' 03"
Powderhorn Granite		
WCG03-40B	38° 17' 41"	107° 05' 36"
Granite of Tolvar Peak		
WCG03-19	38° 20' 18"	107° 07' 59"
Granite of Cebolla Creek		
WCG03-36A	38° 22' 27"	107° 09' 03"
Ferrocarbonatite		
WCG03-22	38° 20' 34"	107° 07' 34"
Monzonite		
WCG03-26	38° 20' 26"	107° 06' 06"

PETROLOGY

Methodology

A total of 42 samples were collected from various lithologies in the study area. Nineteen samples were collected from the various syenitoid intrusions, 6 samples were collected from the mafic and felsic portions of the Dubois Greenstone, 6 samples came from the granite of Tolvar Peak, 2 samples from the Powderhorn Granite, 1 sample of diabase, 3 of monzonite, 3 from a ferrocarbonatite exposure, and 2 samples from a granite and syenitoid outcrop along Cebolla Creek were also collected.

Special attention was taken to obtain syenite samples corresponding to the augite syenite and biotite syenite of Hunter (1925) and the K-Ar analyzed samples of Olson et al. (1977) to allow detailed examination with respect to the sampling of this study. Three of the four locations that Olson et al. (1977) sampled were resampled (Sites A and C) and petrographically and geochemically analyzed, while site C-1 was only petrographically analyzed. Site WCG03-35 corresponds with site A, WCG03-4 is site C, and WCG03 25 corresponds to C-1 of Olson et al. (1977) (Figure 4).

Petrographic thin sections were made for each of the 42 samples at the Earth Science Petrology Preparation Laboratory at UNC Wilmington. A representative set of 10 thin sections were stained for K-feldspar and plagioclase by the method of Bailey and Stevens (1960). A modal analysis of 100 counts each was performed on each of the ten stained thin sections. The modal analyses are summarized in Table 3. Samples were classified on the QAP classification scheme of Le Maitre (2002) (Figure 5).

Amphibolite, felsic schist, and quartzite of the Dubois Greenstone, as well as the granite of Tolvar Peak comprise the majority of the rocks of the study area (Figure 6). Additionally, outcrops of ferrocarbonatite and monzonite (trachyte of Hedlund and Olson, 1975) are found intruding the granite of Tolvar Peak. An additional monzonite crops out along Highway 149. To the south and west of the field area, the Powderhorn Granite crops out. Tertiary Sapinero Mesa Tuff outcrops occur in the northern portion of Wildcat Gulch overlying both the augite syenite and a felsic lithodeme of the Dubois Greenstone. Small Ordovician diabase dikes crosscut the Dubois Greenstone. The Wildcat Gulch syenite intrudes the mafic and felsic portions of the Dubois Greenstone.

Dubois Greenstone

The Dubois Greenstone of the study area has two main lithodemes. The mafic lithodeme of the Dubois Greenstone is green-black colored, fine to coarsely-crystalline amphibolite that ranges from a phyllitic to gneissic microstructure. The mineral assemblage consists of actinolite, quartz, plagioclase, calcite, dolomite, epidote, biotite, garnet, and chlorite. Subidioblastic to idioblastic, acicular to lamellar actinolite crystals are pale green to pale blue in plane-polarized light. Microcrystalline quartz and plagioclase crystals are xenoblastic with quartz having sweeping extinction. Calcite and dolomite crystals are subidioblastic with polysynthetic twinning. Bladed biotite crystals are subidioblastic having parallel extinction. Xenoblastic and microcrystalline epidote exists as a reaction replacement of plagioclase. Minor garnet crystals are idioblastic to subidioblastic having high relief. Minor subidioblastic chlorite crystals are associated with biotite crystals.

Table 3. Modal analysis of petrographic thin sections of selected rocks of the Wildcat Gulch study area. All samples have been stained for K-feldspar and plagioclase using the method of Bailey and Stevens (1960).

Mineral Percents for Feldspar-Stained Thin Sections

	K-feldspar	Plagioclase	Quartz	Biotite	Riebeckite	Hornblende	Augite	Opaque Mineral	Hematite	Apatite	Calcite
Wildcat Gulch Syenite											
WCG03-01	49	32	12	7	np	np	np	np	np	np	np
WCG03-04	39	24	6	11	15	np	< 1	3	np	2	np
WCG03-29A	39	17	4	10	30	np	np	np	np	< 1	np
WCG03-31	38	18	5	9	29	np	< 1	np	np	1	np
WCG03-35A	20	35	6	14	25	np	< 1	np	np	np	np
WCG03-36B	37	19	5	9	30	np	np	np	np	np	np
Powderhorn Granite											
WCG03-40B	40	32	26	2	np	np	np	np	np	np	np
Granite of Tolvar Peak											
WCG03-19	34	32	24	10	np	< 1	np	np	np	np	np
Granite of Cebolla Creek											
WCG03-36A	41	29	19	4	7	np	np	np	np	np	np
Ferrocarbonatite											
WCG03-22	42	np	4	np	np	np	np	np	32	np	22
Monzonite											
WCG03-26	32	58	4	np	np	np	np	6	np	np	np

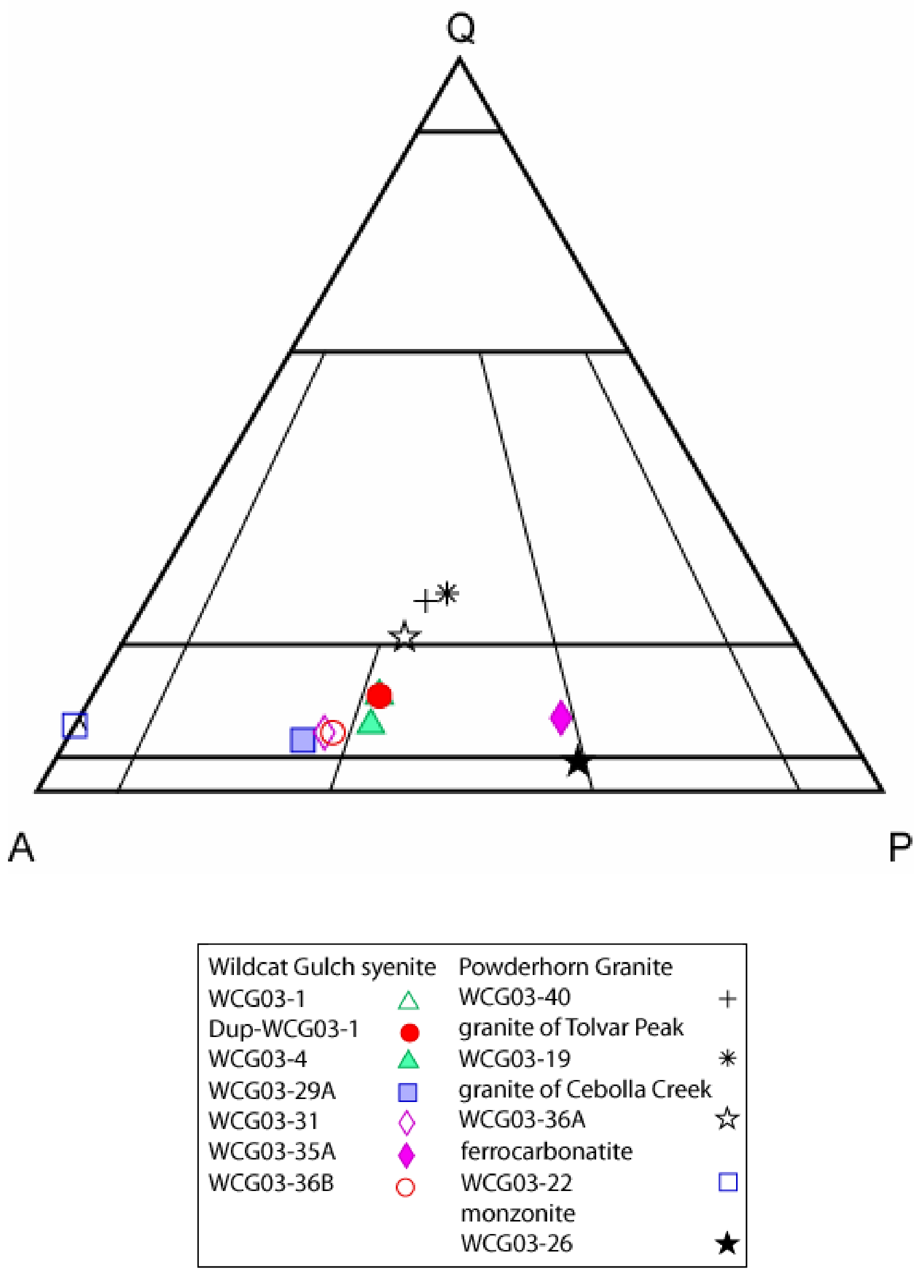


Figure 5. Quartz versus alkali-feldspar versus plagioclase (QAP) classification of Le Maitre (2002) for the Wildcat Gulch samples.

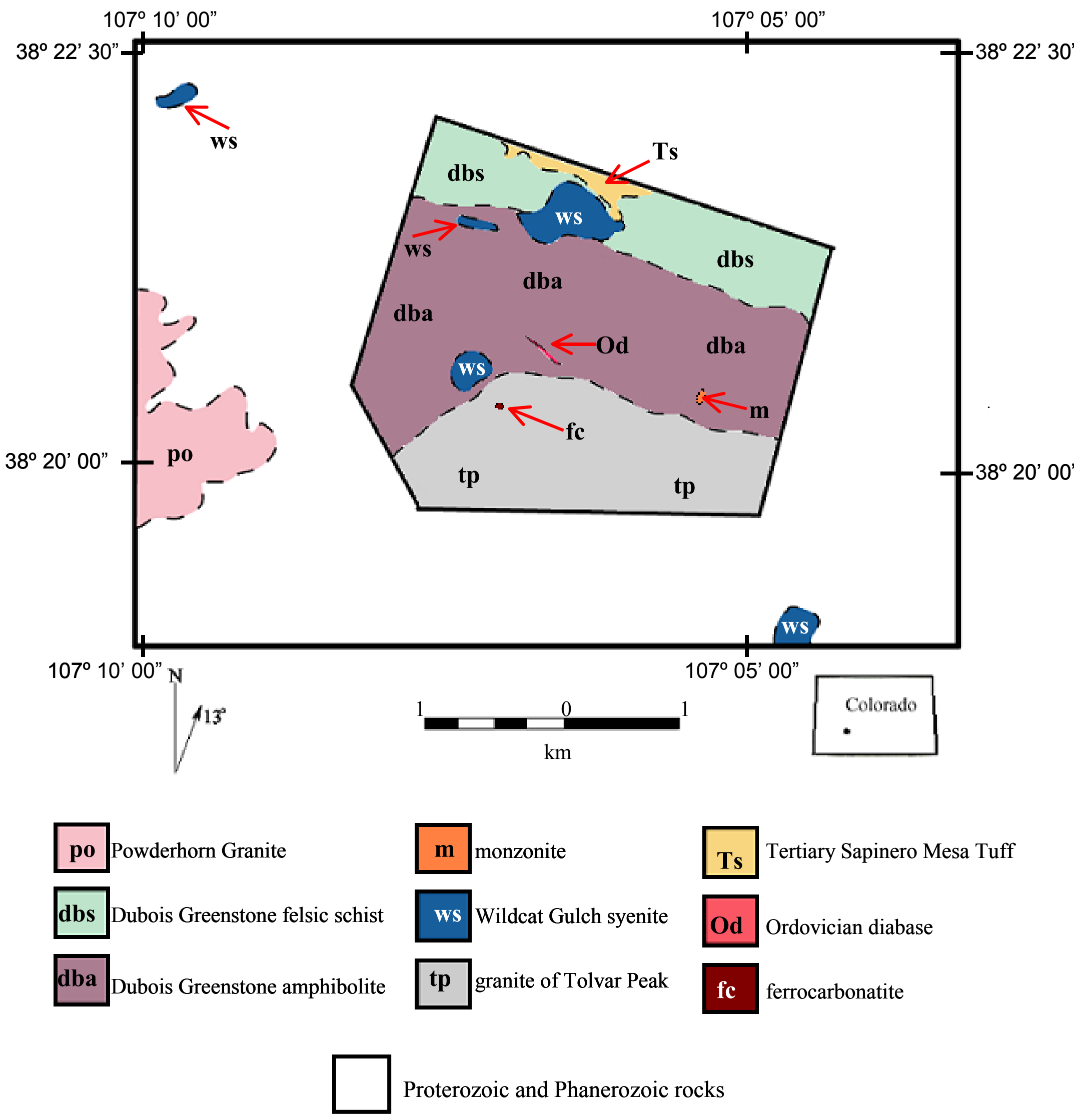


Figure 6. Geologic map of the Wildcat Gulch study area. The Powderhorn Granite outcrop has been adapted from Olson and Hedlund (1973) and Hedlund and Olson (1975). The contacts are inferred due to the limited exposures. The study area is outlined in black.

The mafic lithodeme has an east-west striking, subvertical foliation. Isoclinal folding is present within a phyllitic outcrop in the western portion of the study area. Some of the samples have relict plagioclase phenocrysts reacting to form epidote and quartz. Copper mineralization in some locations has produced variably abundant malachite.

The protolith for the mafic lithodeme of the Dubois Greenstone is thought to be basalt flows or, in some cases, gabbro (Condie and Nuter, 1981; Hedlund and Olson, 1981; Nelson and Riesmeyer, 1983). This study agrees with these authors on the protolith determination for the mafic portion of the Dubois Greenstone based upon the relict pillow structures seen in some outcrops east of the field area. In addition, the coarse grained nature of some amphibolite outcrops may suggest either metamorphic recrystallization or a gabbroic protolith.

The felsic lithodeme of the Dubois is white to tan, finely-crystalline schist. The mineralogic assemblage consists of quartz, K-feldspar, plagioclase, and white mica. Microcrystalline quartz crystals are xenoblastic. K-feldspar and plagioclase crystals are subidioblastic to xenoblastic. Minor bladed white mica crystals are subidioblastic to idioblastic. Some samples contain relict quartz phenocrysts and compositional layering suggesting an extrusive volcanic protolith.

The felsic lithodeme is often intercalated with the mafic lithodeme of the Dubois Greenstone and has the same east-west trend and subvertical foliation. Condie and Nuter (1981) hypothesize that the protolith of the felsic lithodeme is rhyolitic lava flows and tuffs. However, the majority of the felsic lithodeme within the field area appears to have a more felsic tuff protolith as opposed to lava flow protolith based upon the small to microcrystalline nature of the minerals, and the presence of relict phenocrysts.

Within the mafic, and to a lesser extent the felsic lithodemes of the Dubois Greenstone, there are discontinuous lenses of varied colored, finely-to coarsely-crystalline, granular quartzite. These erosionally resistant lenses are oriented east-west and concordant to the foliation. Most quartzite lenses are nonfoliated to weakly foliated. These quartzite lenses are interpreted these to be seafloor bedded cherts based upon their interbedded nature within the mafic and felsic lithodemes of the Dubois Greenstone (Nelson and Riesmeyer, 1983; Boardman, 1986).

Granite of Tolvar Peak

The granite of Tolvar Peak sample is a pink and gray colored, medium-crystalline, leucocratic, holocrystalline, hypidiomorphic granular, non-foliated rock. The mineral assemblage from the modal analysis is 34% K-feldspar (microcline), 32% plagioclase, 24% quartz, 11% biotite, <1%, hornblende, and <1% white mica (Tables 3 and 4). A trace amount of apatite was found only in one sample. Microcline is anhedral to subhedral having minor tartan plaid twinning. The microcline crystals are lath shaped having a myrmekitic texture with quartz inclusions. The lath-shaped plagioclase is anhedral to subhedral and has no twinning. There is some sericitization and saussauritization of microcline and plagioclase. Quartz crystals are anhedral having sweeping extinction. The lath-shaped biotite crystals are subhedral having parallel extinction. Minor hornblende crystals are subhedral to euhedral with inclined extinction. Minor apatite crystals are subhedral to anhedral having a high relief and parallel extinction.

The granite of Tolvar Peak in the field area varies in color and percentage of quartz. In the southeast portion of the map area, the granite is white to pink in color with approximately 20 % quartz. Westward, the color of the granite darkens to red while the percentage of quartz increased to approximately 40 %.

Table 4. Summary of major (>5 modal percent) and accessory (< 5 modal percent) minerals in representative samples of the intrusive units of the Wildcat Gulch study area.

	Major Minerals							Accessory Minerals
	K-feldspar	Plagioclase	Quartz	Biotite	Riebeckite	Hematite	Calcite	
Wildcat Gulch Syenite								
WCG03-01	X	X	X	X				
WCG03-04	X	X	X	X	X			opaque mineral, apatite
WCG03-29A	X	X	X	X	X			apatite
WCG03-31	X	X	X	X	X			apatite
WCG03-35A	X	X	X	X	X			
WCG03-36B	X	X	X	X	X			
Powderhorn Granite								
WCG03-40B	X	X	X					biotite
Granite of Tolvar Peak								
WCG03-19	X	X	X	X				hornblende, epidote
Granite of Cebolla Creek								
WCG03-36A	X	X	X		X			biotite
Ferrocarbonatite								
WCG03-22	X					X	X	quartz
Monzonite								
WCG03-26	X	X	X					opaque mineral, epidote

Based upon the classification scheme of Le Maitre (2002), the granite of Tolvar Peak sample falls within the granite field (Figure 5, WCG03-19).

Powderhorn Granite

The Powderhorn Granite sample is a pink to gray green, medium-crystalline, leucocratic, holocrystalline, hypidiomorphic granular, non-foliated rock. The mineral assemblage (Table 4) is 40 % K-feldspar (microcline), 23 % plagioclase, and 26 % quartz with 2 % biotite (Table 3). Lath-shaped microcline crystals are anhedral to subhedral having minor tartan plaid twinning. The lath-shaped plagioclase crystals are anhedral to subhedral having no visible twinning. Quartz crystals are anhedral having sweeping extinction. The lath-shaped biotite crystals are anhedral to subhedral having parallel extinction. Based upon classification scheme of Le Maitre (2002), the Powderhorn sample falls into the granite field (Figure 5, WCG03-40).

The Powderhorn Granite described by Olson and Hedlund (1973) and Hedlund and Olson (1975) is a light pink, medium-to coarse-grained, weakly foliated to gneissic granite. Most mapped outcrops of the Powderhorn Granite by Olson and Hedlund (1973) and Hedlund and Olson (1975) within the vicinity of the field area were observed in this study to be light pink to tan, finely-crystalline, felsic schist. This schistosity may be the foliation that Olson and Hedlund (1973), Hedlund and Olson (1975), and Nelson and Riesmeyer (1983) describe. However, these schistose outcrops should not be referred to as granite because they show no original phaneritic granitoid texture. They primarily appeared to be felsic schist having a possible volcanic protolith because they were so finely crystalline. In addition, these finely-crystalline schist outcrops contained no phenocrysts. This lack of phenocrysts suggests that they formed as extrusive igneous rocks, possibly as felsic tuffs. If there were phenocrysts present, then it is possible to suggest that they formed from a granite or hypabyssal intrusion that was later metamorphosed and foliated.

Wildcat Gulch Syenite

Within the Wildcat Gulch study area, there are six intrusions of syenitoid rocks mapped by Olson and Hedlund (1973) and Hedlund and Olson (1975). These syenitoid rocks include augite syenite, biotite syenite, melasyenite, and quartz syenite and syenite (Olson and Hedlund, 1973; Hedlund and Olson, 1975). The syenitoid rocks of this study were field classified as leucocratic syenitoid and melanocratic syenitoid based upon mineralogy and color index. Figure 7 illustrates the differences in the boundaries of the syenitoid rocks from the mapping of Olson and Hedlund (1973) and Hedlund and Olson (1975) to the syenitoid boundaries mapped in this study.

Only one body of leucocratic syenitoid occurs within the study area. This is exposed as patches of float material and larger blocks at the top of a hill (Figure 8). The leucocratic syenitoid sample is a light pink to tan colored, fine-to medium-crystalline, holocrystalline, hypidiomorphic granular, non-foliated rock. The mineral assemblage consists of 49 % K-feldspar (microcline), 32 % plagioclase, 12 % quartz, and 7 % biotite (Tables 3 and 4). Microcline is subhedral and columnar to granular in form having zoned extinction, and tartan plaid twinning. Plagioclase is subhedral to anhedral having a sweeping extinction and no twinning. The interstitial anhedral quartz has a sweeping extinction. The subhedral bladed biotite crystals have parallel extinction.

On the classification scheme of Le Maitre (2002), this rock plots as a quartz monzonite (Figure 5, WCG03-1).

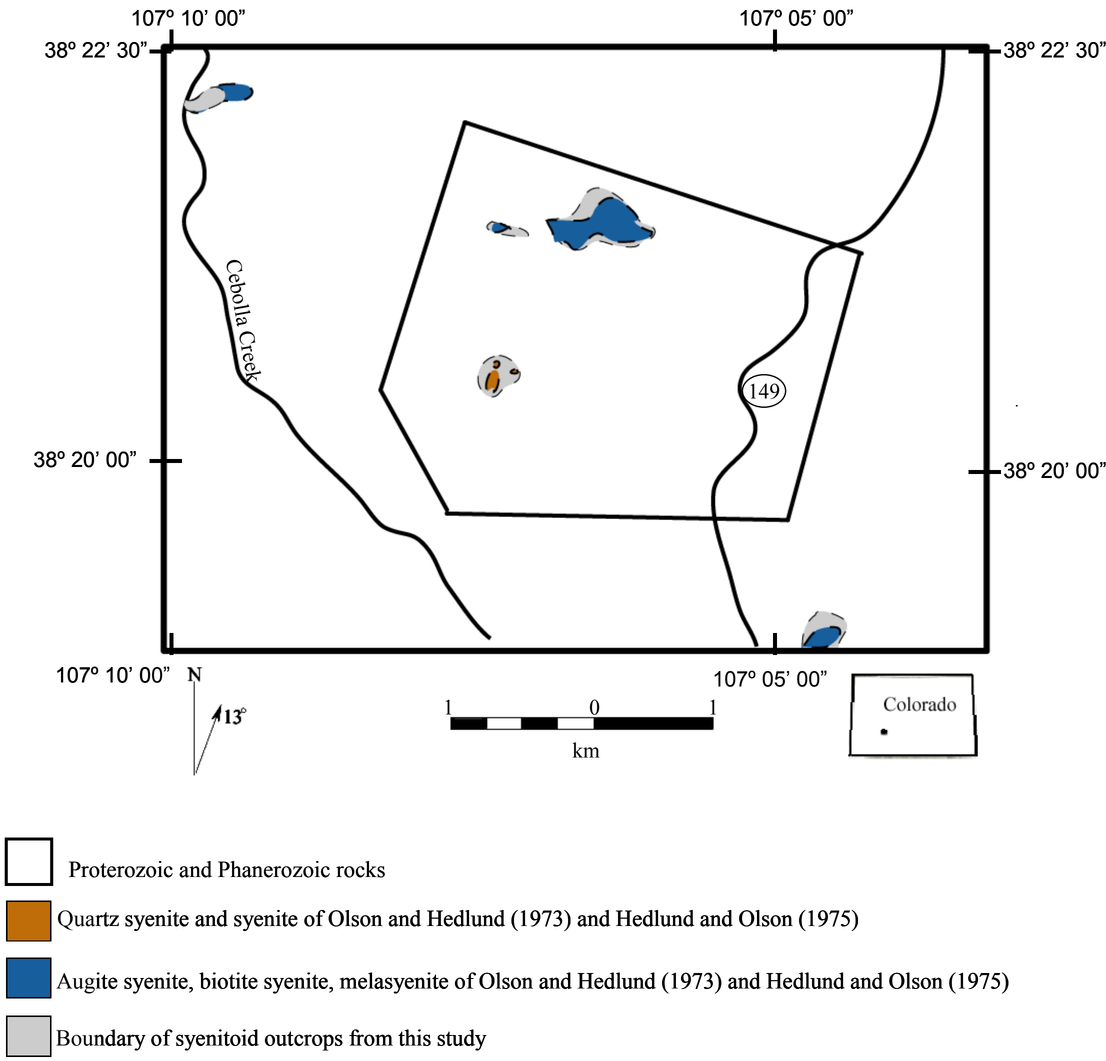


Figure 7. Geologic map of the boundaries of various syenitoid intrusions in the Wildcat Gulch study area. The blue and brown colored syenitoid outcrops were adapted from Olson and Hedlund (1973) and Hedlund and Olson (1975).

Figure 8. View to the north west of the leucocratic quartz monzonite exposure intruding rocks of the Dubois Greenstone. Outcrop is located approximately 1 km south of Spencer. Sample WCG03-1 collected near the crest of the hill. The outcrop is approximately outlined in red.

This leucocratic quartz monzonite intrudes the felsic Dubois Greenstone lithodeme, and it contains an amphibolite enclave that is approximately one meter in diameter. This enclave is finely crystalline, weakly foliated, and contains subhedral, bladed to acicular actinolite, anhedral plagioclase, anhedral epidote, and microcrystalline, anhedral quartz crystals. This amphibolite enclave is both mesoscopically and microscopically similar to the amphibolite of the Dubois Greenstone mafic lithodeme.

The majority of the syenitoid in the Wildcat Gulch study area consist of melanocratic syenitoid outcrops. In outcrop, these rocks are blocky to rounded in shape, and are somewhat resistant to erosion (Figure 9). The melanocratic syenitoid samples are dark green and pink mottled, medium- to coarsely-crystalline, holocrystalline, hypidiomorphic granular, non-foliated rocks. The mineral assemblage consists of 20 and 39 % K-feldspar (microcline), 17 to 35 % plagioclase, 15 to 30 % riebeckite, 9 to 14 % biotite, and 4 to 6 % quartz, with < 2% apatite, < 1 % augite, and < 1 % zircon. (Figure 10; Tables 3 and 4). Epidote is also present in some samples as a secondary reaction replacement of plagioclase. Microcline is subhedral and columnar to granular in form having a zoned extinction, and minor tartan plaid twinning. Plagioclase is anhedral having a sweeping extinction and no twinning. The riebeckite is bladed to acicular and subhedral having inclined extinction and pale green to blue green pleochroism. The subhedral, bladed biotite crystals have parallel extinction and minor inclusions of high relief, rectangular pale brown to black euhedral rutile. The interstitial, anhedral quartz has a sweeping extinction. Apatite crystals are subhedral to anhedral having a high relief and parallel extinction. Blocky augite crystals are subhedral having epitaxial riebeckite overgrowths that completely surround the augite. Some blocky to acicular riebeckite crystals contain epitaxial biotite overgrowths.

Figure 9. Typical melanocratic syenitoid outcrop with white colored felsic schist of the Dubois Greenstone located approximately 250 m west of Spencer. View is to the south. Arrows indicate the melanocratic syenitoid. Note the typical rounded weathering pattern within the syenitoid. Sample WCG03-31 collected from the exposure. Rock hammer for scale is 40 cm long.

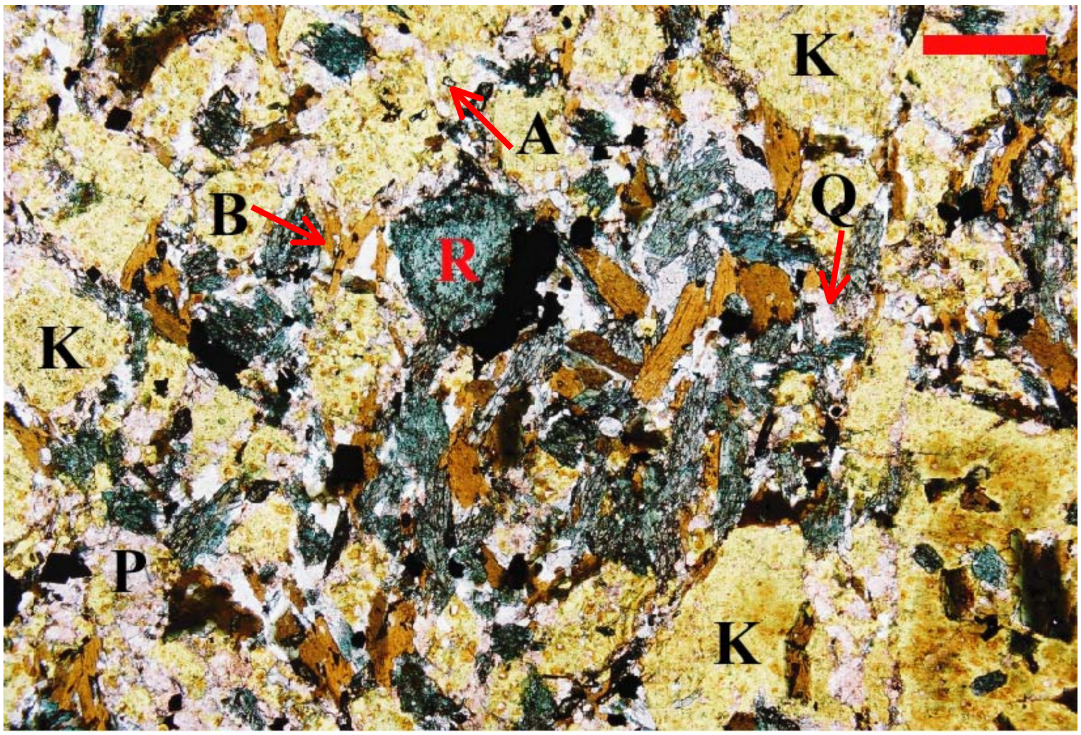


Figure 10. Photomicrograph of feldspar-stained thin section in plane-polarized light of sample WCG03-04. “Q” is quartz; “K” is K-feldspar; “P” is plagioclase; “R” is riebeckite; “B” is biotite; “A” is apatite. Field of view is 9 mm; red scale bar is 1 mm.

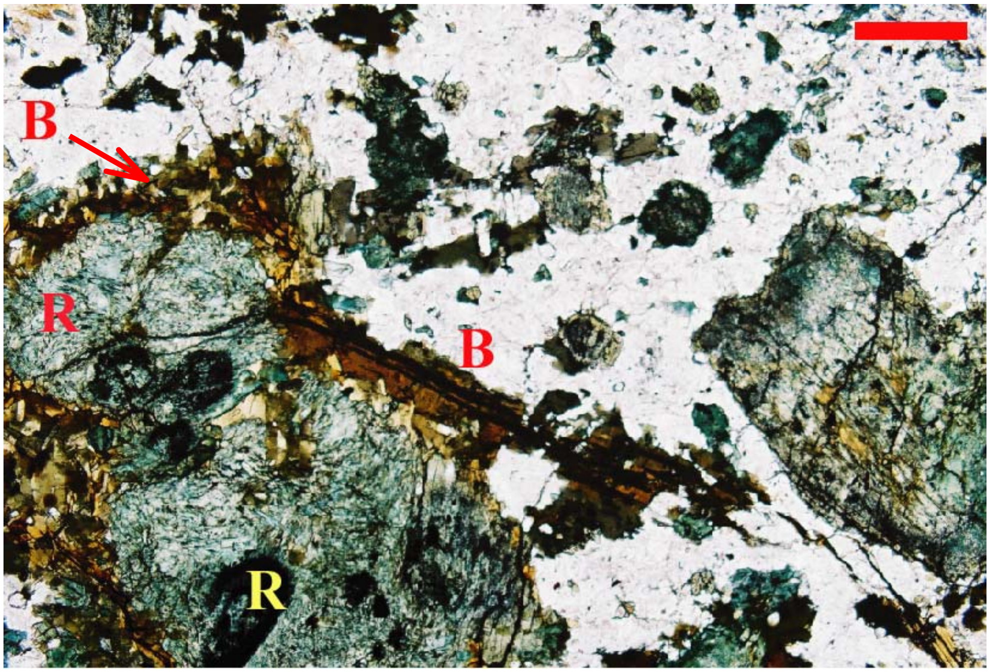
These biotite crystals completely surround the riebeckite (Figure 11). In many areas the biotite is altered to vermiculite and can also have a very cloudy appearance.

Based on classification scheme of Le Maitre (2002), the melanocratic syenitoid ranges from quartz syenite to quartz monzonite (Figure 5).

Along Cebolla Creek, approximately 2 km west of the study area, there is a syenitoid outcrop that Olson and Hedlund (1973) mapped as a porphyritic augite syenite surrounded by melasyenite. This syenitoid is informally named here the syenite of Cebolla Creek. This sample is a dark green, medium-crystalline, mesocratic, riebeckite-rich rock. The mineral assemblage consists of 37 % K-feldspar (microcline), 30 % riebeckite, 29 % plagioclase, 9 % biotite, and 5 % quartz (Tables 3 and 4). Microcline is subhedral and columnar in form having a zoned extinction, and tartan plaid twinning. Riebeckite is acicular and subhedral having inclined extinction. Plagioclase is anhedral having a sweeping extinction and no twinning. Subhedral bladed biotite crystals have parallel extinction. Interstitial anhedral quartz has a sweeping extinction.

A pink and green, medium-to coarsely-crystalline, leucocratic granite containing biotite and riebeckite is complexly intercalated with this quartz syenite. This, informally named, granite of Cebolla Creek contains 41 modal % K-feldspar (microcline), 29 modal % plagioclase, and 19 modal % quartz, with 7 modal % riebeckite and 5 modal % biotite (Tables 3 and 4). Lath-shaped microcline is subhedral having tartan plaid twinning. Plagioclase is anhedral to subhedral and has no twinning. Quartz crystals are anhedral having sweeping extinction. Riebeckite crystals are acicular and subhedral. The lath to bladed shaped biotite crystals are subhedral having parallel extinction.

a.



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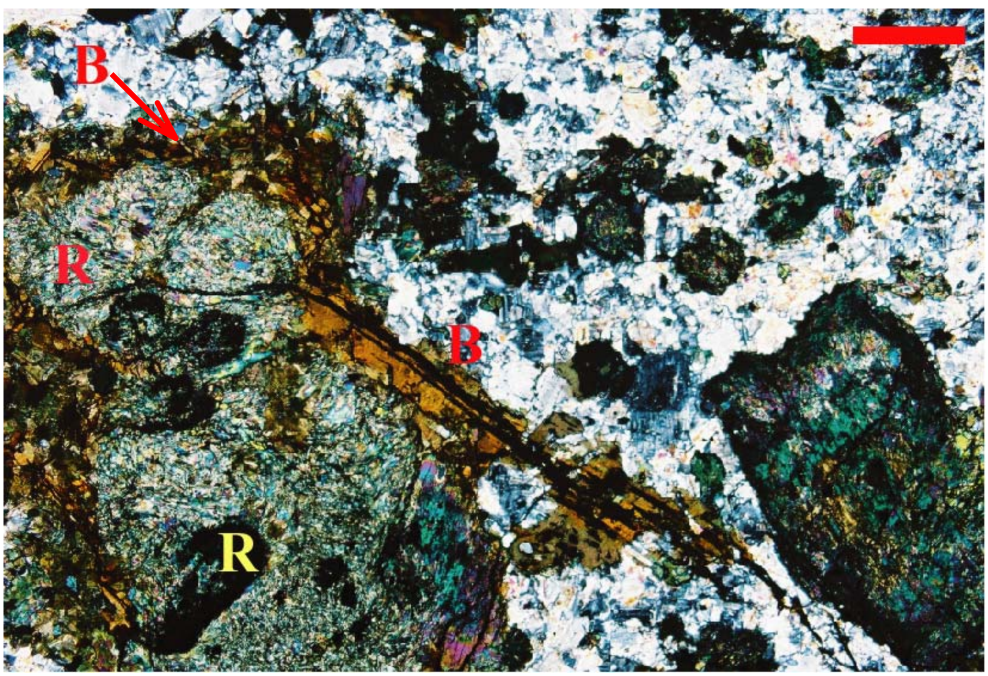


Figure 11. Photomicrograph of melanocratic syenitoid in: a) plane-polarized and b) cross-polarized light. “B” is biotite; “R” is riebeckite. Field of view is 9 mm; red scale bars are 1 mm.

According to the classification scheme for igneous rocks of Le Maitre (2002), the syenite of Cebolla Creek is classified as a quartz syenite and the granite of Cebolla Creek is classified as a granite (Figure 5).

Included in the biotite syenite of Hedlund and Olson (1975) is a biotite-calcite syenite dike (C-1 of Olson et al., 1977). This outcrop is a thin dike less than 1 m wide containing plagioclase, quartz, riebeckite, biotite, and calcite (WCG03-25; Figure 12). Plagioclase crystals are anhedral to subhedral having sweeping extinction and a myrmekitic texture. Quartz is anhedral having sweeping extinction and minor rutile inclusions. Riebeckite crystals are subhedral with inclined extinction. Bladed subhedral biotite crystals have parallel extinction. Euhedral to subhedral calcite crystals are minor.

Olson et al. (1977) classify this rock is a biotite-calcite syenite dike. In order to refer to this outcrop as a syenite, it must contain K-feldspar. However, no K-feldspar was found in the collected sample.

Additionally, within the study area, leucocratic syenitoid dikes up to a 4 cm thick containing quartz and K-feldspar (microcline) crosscut the melanocratic quartz syenite and quartz monzonite (Figures 13 and 14). Both the quartz and microcline have sweeping extinction and a cloudy brown to almost opaque color giving the minerals a shaded appearance. The quartz is anhedral and the microcline is subhedral with minor tartan plaid twinning. These crosscutting rocks are similar to the leucocratic quartz monzonite in appearance and mineralogy, but they lack biotite.

In comparison to the syenitoid intrusions of Olson and Hedlund (1973) and Hedlund and Olson (1975), the leucocratic quartz monzonite is very similar to the quartz syenite and syenite

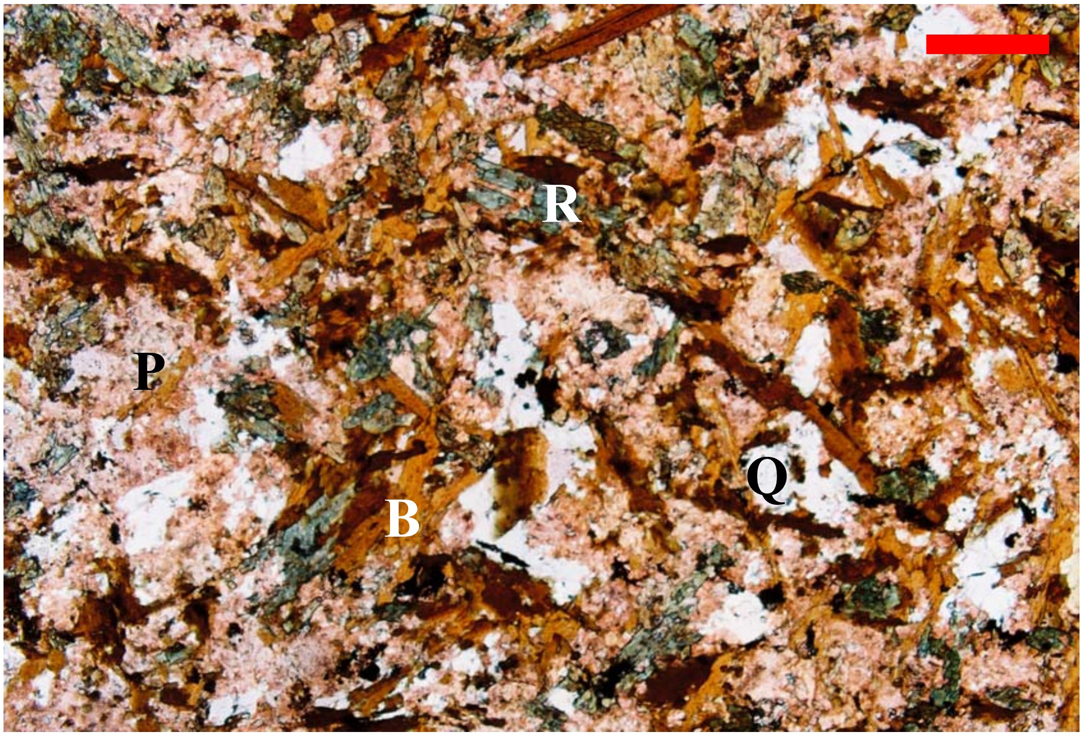


Figure 12. Photomicrograph of feldspar-stained thin section in plane-polarized light of WCG 03-25a (biotite calcite syenite dike of Hedlund and Olson (1975)). "Q" is quartz; "P" is plagioclase; "R" is riebeckite; "B" is biotite. Field of view is 9 mm; red scale bar is 1 mm.

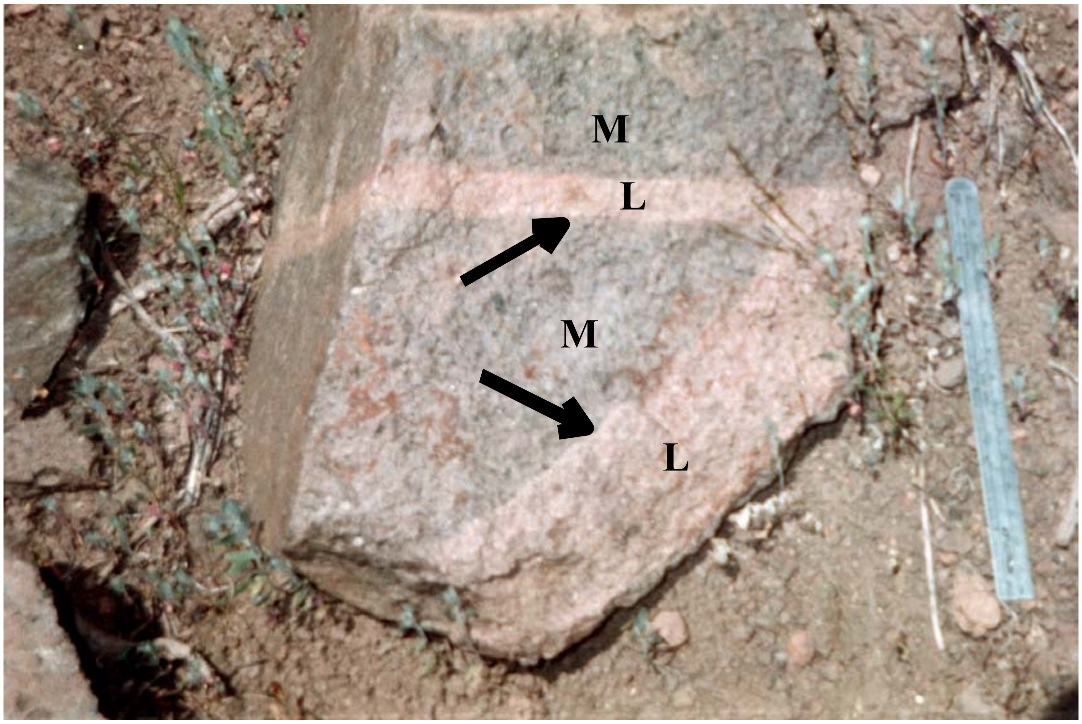
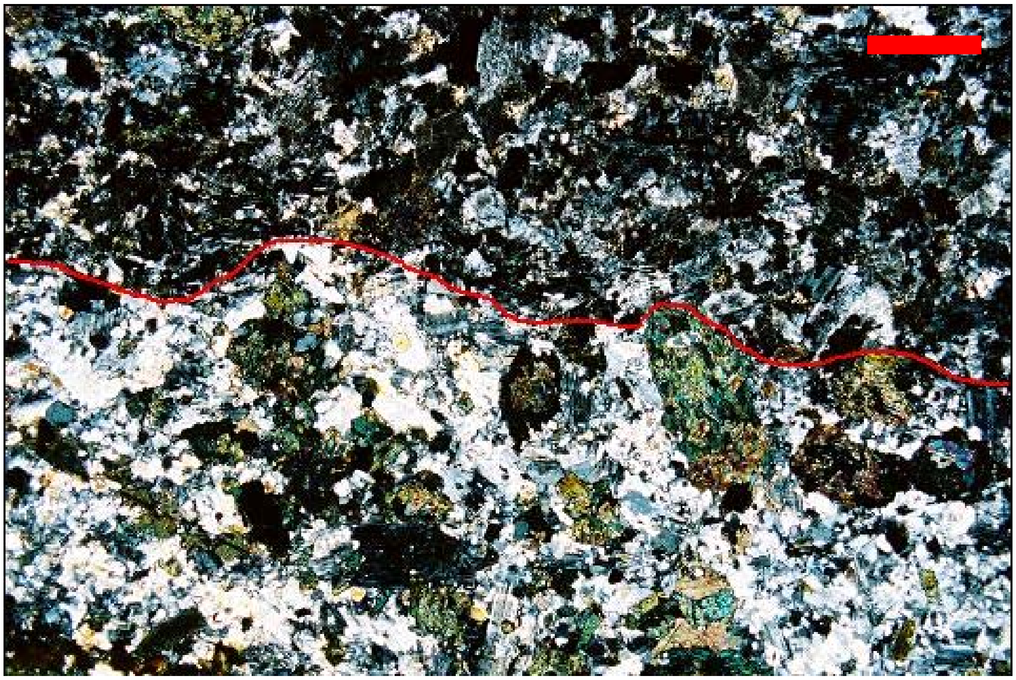


Figure 13. Leucocratic syenitoid dike (L) crosscutting a melanocratic syenitoid (M), north of Wildcat Gulch, and approximately 250 m west of Spencer. Scale bar is 15 cm long; arrows indicate the dike.

a.



b.

Figure 14. Photomicrographs of the contact between the melanocratic syenitoid and the leucocratic syenitoid dike in: a) plane-polarized and b) cross-polarized light. Red line indicates the boundary between the lower melanocratic syenitoid and the upper leucocratic syenitoid dike. This dike crosscuts the melanocratic syenite. Field of view is 9 mm; red scale bars are 1 mm.

description of Hedlund and Olson (1975). The quartz syenite and syenite of Olson and Hedlund (1973) and Hedlund and Olson (1975) is a light pink, microcline-rich rock having up to 15 modal % quartz and 10 modal % biotite. Hedlund and Olson (1975) further state that the quartz syenite and syenite crosscuts their augite syenite and is therefore younger (Hedlund and Olson, 1975). This observation agrees with the intrusive nature of leucocratic syenitoid dikes within the melanocratic quartz syenite and quartz monzonite samples.

The melanocratic quartz syenite and quartz monzonite samples are similar to the biotite syenite and augite syenite of Olson and Hedlund (1973) and Hedlund and Olson (1975). They describe these rocks as containing 45 to 70 % microcline, 35 % biotite, 20 % augite, and 20 % hornblende (Olson and Hedlund, 1973; Hedlund and Olson, 1975).

Curiously, Olson and Hedlund (1973) and Hedlund and Olson (1975) do not indicate the presence of any plagioclase. In this study, these lithologies were found to contain 17 to 35% plagioclase. It is possible that Hedlund and Olson (1975) may not have stained for feldspars and therefore did not see plagioclase in the lithologies.

In addition, the mineral nepheline was not present in any samples of this study, and was not present in the syenite descriptions of Olson and Hedlund (1973) and Hedlund and Olson (1975)

Ferrocarbonatite

Within the granite of Tolvar Peak, an outcrop of carbonatite (WCG03-22) is exposed in the extreme southern portion of the Wildcat Gulch study area. This small outcrop (3 m by 3 m) occurs within a Fe prospect pit. This prospect pit contains numerous float samples of specular hematite, and the carbonatite also contains specular and massive hematite. The carbonatite sample is a pink to gray and brown, holocrystalline, porphyritic, K-feldspar-rich rock. The mineral assemblage is 42 % K-feldspar, 32 % hematite, 22 % calcite, and 4 % quartz (Figure 15; Tables 3 and 4). Subhedral to euhedral K-feldspar crystals, primarily occurring as phenocrysts up to 5 mm by 9 mm in size, are columnar to lath shaped having sweeping extinction and no twinning. It is uncertain which type of K-feldspar is present due to the lack of twinning.

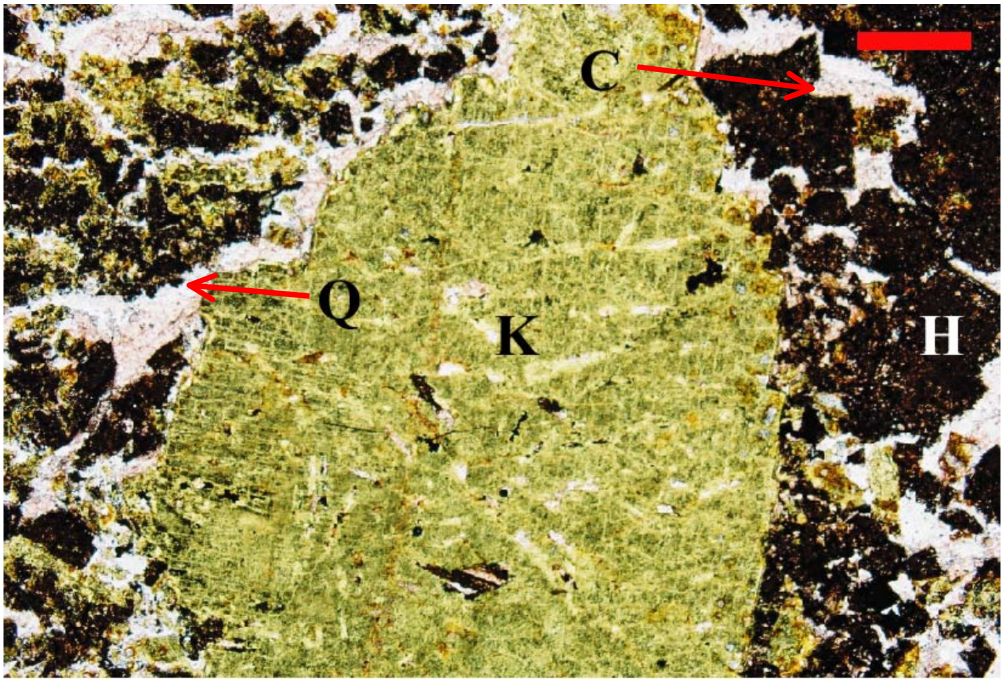
Hematite is red-brown to opaque having high relief. Subhedral hematite has plate shaped crystals while anhedral hematite forms masses of crystals. Calcite crystals are anhedral to subhedral. The interstitial quartz is microcrystalline and anhedral having sweeping extinction.

Based upon the classification scheme of Le Maitre (2002) this rock is classified as a ferrocarbonatite.

Monzonite

The monzonite (trachyte of Hedlund and Olson (1975)) occurs as thin (< 2 m wide) dikes within the mafic lithodeme of the Dubois Greenstone and the granite of Tolvar Peak (Figure 16). The monzonite samples are light pink to orange colored, leucocratic, holocrystalline rocks. The samples have a pilotaxitic to trachyitic and porphyritic texture. The mineral assemblage consists of 59 % plagioclase, 29 % K-feldspar, and 6 % quartz (Tables 3 and 4). The phenocrysts and groundmass are plagioclase rimmed with K-feldspar (anti-rapikivi texture; Figure 17). The plagioclase is subhedral to euhedral forming bladed laths to acicular crystals in the groundmass having near parallel extinction. The K-feldspar crystals are anhedral having sweeping extinction and no twinning. The K-feldspar crystals are acicular in the groundmass and bladed as small phenocrysts. The interstitial quartz is microcrystalline, anhedral, and has

a.



b.

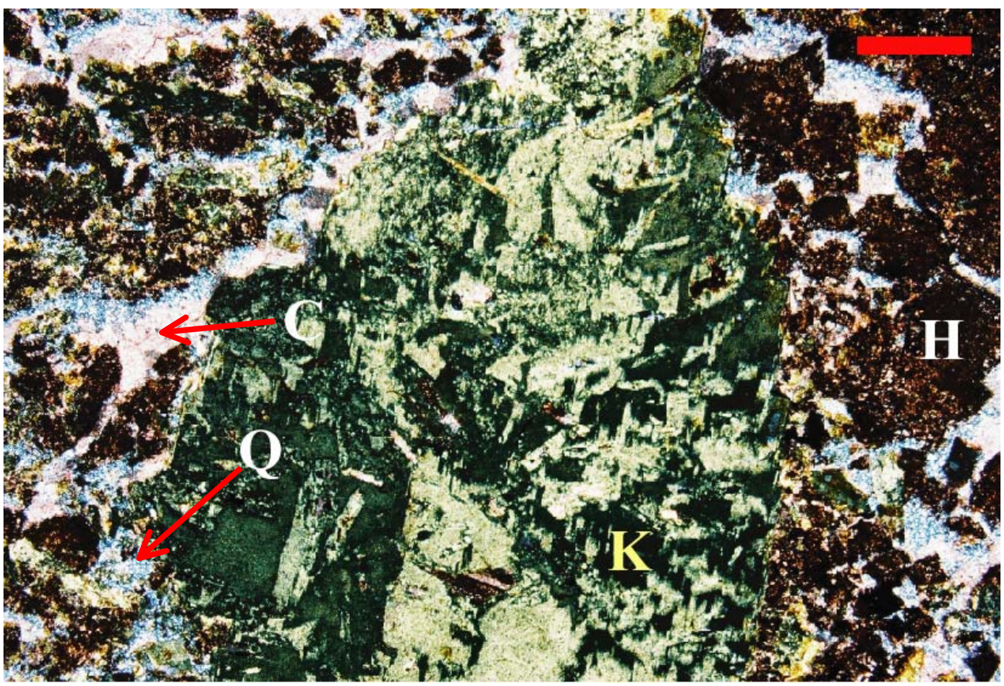


Figure 15. Photomicrograph of feldspar-stained thin section of WCG 03-10 (ferrocarbonatite) in: a) plane-polarized and b) cross-polarized light. “Q” is quartz; “K” is K-feldspar; “C” is calcite; “H” is hematite. Field of view is 9 mm; red scale bars are 1 mm.

Figure 16. Monzonite outcrop (WCG 03-26) located along Highway 149 at the top of Nine Mile Hill. View is to the southwest. Arrows indicate monzonite outcrop in contact with the mafic lithodeme of the Dubois Greenstone in the field area. Monzonite crosscuts the foliation of the mafic lithodeme of the Dubois Greenstone.

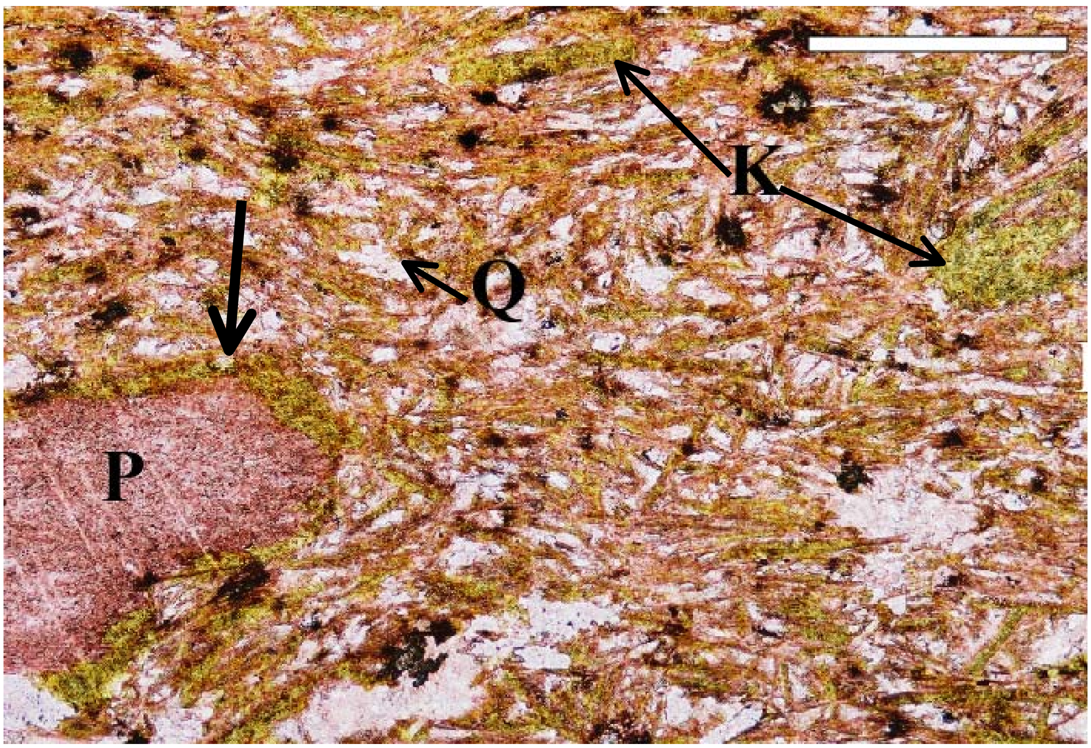


Figure 17. Thin section in plane-polarized light of WCG 03-26 (monzonite). "Q" is quartz; "K" is K-feldspar; "P" is plagioclase. Large black arrow indicates anti-rapikivi texture. Field of view is 4.25 mm; white scale bar is 1 mm.

sweeping extinction. Minor anhedral and microcrystalline epidote and opaque minerals occur in the groundmass.

The overall color of the rock is red, which would suggest that K-feldspar was the dominant feldspar. However, staining indicates that the dominant feldspar is plagioclase and K-feldspar forms rims around the plagioclase as anti-rapikivi texture (Figure 17).

Hedlund and Olson (1975) called this rock a trachyte. However, due to the abundance of plagioclase versus K-feldspar, these rocks would be more accurately classified as a monzonite (Figure 5).

Diabase Dikes

In the southern portion of the Wildcat Gulch study area, there are fine to medium-crystalline, black to brown (weathered), melanocratic diabase dikes. These thin (< 3 m wide) dikes crop out within the Dubois Greenstone, and they have an east-west orientation parallel to the regional foliation. The mineral assemblage includes acicular plagioclase and augite.

Sapinero Mesa Tuff

The tuff, located in the northern portion of the area, unconformably overlies the felsic lithodeme of the Dubois Greenstone and a melanocratic syenitoid outcrop (Figure 4). The tuff has a range in colors, and the amount and type of lithic fragments vary. They are purple to pink to brown to gray, porphyritic, felsic to intermediate, crystal-lithic tuff. Phenocrysts include subhedral plagioclase, subhedral quartz, and bladed, subhedral biotite crystals. Lithic fragments are tuff, pumice fragments, and amphibolite. Some of the glass is devitrified to quartz. Some welding is present in these samples, but flow is not evident in all samples. These rocks are ash fall tuff and pryroclastic (or laharic) flows. These rocks are classified as crystal-lithic rhyolitic tuffs according to the classification scheme of Le Maitre (2002).

GEOCHEMISTRY

Methodology

Six syenitoid samples, three granite samples, one monzonite, and one ferrocarbonatite sample, were selected for major and trace element geochemical analyses. Weathering rinds or loose debris were removed from the samples. The cleaned samples were crushed using a 600 lb hydraulic jack and chipped using a steel-plated jaw crusher. The chips were then cleaned using deionized water in an ultrasonic cleaner. After rinsing and cleaning, the samples were air dried on a hot plate. Once completely dry, the samples were powdered using an aluminoceramic SPEX™ shatterbox and sent to SGS Minerals XRAL laboratories in Ontario, Canada for major and trace element geochemical analyses by X-ray fluorescence (XRF), neutron activation analysis, ICP/MS, and AA spectrophotometry. All geochemical plots of the Wildcat Gulch data were performed using IgPet 2001 software.

The data for the Wildcat Gulch syenite were compared to a known group of syenite data from the Zuni Mountains in New Mexico, the Sugarloaf Syenite from Colorado, and other syenite intrusions from Sorenson (1974), McLemore and McKee (1989), and Beane and Wobus (1999) (Table 5). In addition, the syenite samples were compared to the syenite data of Hunter (1925) and the syenite and granite data of Hedlund and Olson (1981) (Table 6). The data for the mafic and felsic lithodemes of the Dubois Greenstone from Condie and Nuter (1981) were also used for comparison with the Wildcat Gulch rocks (Table 7). These comparisons could only be done in terms of the major element oxide data because this study provides the first trace element geochemical data for both the syenitoid intrusions and the related plutonic rocks of the region. Furthermore, results for the Wildcat Gulch syenite samples were compared to the granite of Tolvar Peak and Powderhorn Granite to evaluate the possibility that the Wildcat Gulch syenite

Table 5. Syenite comparison data from Sorenson (1974), Hedlund and Olson (1981), McLemore and McKee (1989), and Beane and Wobus (1999). “Ne. syenite” refers to nepheline syenite. "—" is not reported. Values for major element oxides are reported in weight percent.

Syenite data from Sorenson (1974)

Sample	Syenite	Syenite	Ne. syenite	Ne. syenite	Ne. syenite	Trachyte
SiO_2	58.26	61.86	53.34	56.96	52.73	61.95
Al_2O_3	16.45	16.91	20.10	22.29	23.71	18.03
CaO	3.48	2.54	2.40	1.41	2.54	1.89
MgO	0.87	0.96	0.78	0.51	0.24	0.63
Na_2O	5.52	5.46	8.46	6.52	7.78	6.55
K_2O	5.01	5.91	5.77	7.07	8.08	5.53
Fe_2O_3	1.52	2.32	3.58	1.27	1.89	2.33
MnO	0.15	0.11	0.23	0.08	0.06	0.13
TiO_2	1.31	0.58	0.83	0.42	0.51	0.73
P_2O_5	0.37	0.19	0.25	0.09	0.05	0.18
Total	92.94	96.84	95.74	96.62	97.59	97.95

Syenite Data from the Zuni Mountains from McLemore and McKee (1989)

Sample	Z-3	Z-5	Z-9	Z-10	Z-14	Z-16
SiO_2	60.30	60.20	58.10	53.40	57.70	62.00
Al_2O_3	19.20	18.40	19.80	18.30	18.90	18.60
CaO	0.19	0.21	0.18	0.42	0.41	0.17
MgO	0.93	0.61	0.64	7.39	2.68	0.87
Na_2O	0.19	0.11	0.23	0.09	0.21	0.34
K_2O	14.40	14.80	14.00	11.00	13.10	15.10
Fe_2O_3	3.08	4.32	5.60	7.09	4.14	1.38
FeO	1.22	0.47	0.72	1.60	0.51	0.48
MnO	0.04	0.04	0.04	0.10	0.06	0.03
TiO_2	0.22	0.25	0.26	0.57	0.33	0.13
P_2O_5	0.06	0.07	0.07	0.15	0.11	0.04
LOI	1.12	0.77	1.18	0.43	2.56	0.45
Total	100.95	100.25	100.82	100.54	100.71	99.59

Syenite Data from the Zuni Mountains from McLemore and McKee (1989)

Sample	Z-17	Z-sy	Z-24	Z-27	Z-29	Z-30
SiO_2	62.90	57.30	57.90	69.10	64.80	70.00
Al_2O_3	18.10	19.70	17.60	13.80	16.20	13.20
CaO	0.14	0.27	0.27	1.38	2.05	1.36
MgO	0.22	2.46	0.59	1.14	1.73	1.04
Na_2O	0.40	0.23	0.33	3.09	3.04	3.15
K_2O	15.60	13.80	14.00	5.41	6.33	4.41
Fe_2O_3	2.28	4.09	6.64	3.03	1.46	2.25
FeO	0.32	--	0.40	2.23	2.82	1.98
MnO	0.03	0.05	0.05	0.10	0.08	0.09
TiO_2	0.12	0.34	0.44	0.72	0.79	0.63
P_2O_5	0.02	0.12	0.14	0.15	0.22	0.14
LOI	0.43	2.09	1.00	0.20	1.35	0.96
Total	100.56	100.45	99.36	100.35	100.87	99.21

Syenite data from the Sugarloaf Syenite from Beane and Wobus (1999)

Sample	GM12	GM18	GM19	GM21	GM23	GM31
SiO_2	63.79	63.21	61.44	60.77	63.41	72.24
Al_2O_3	16.83	15.41	15.18	14.89	16.09	13.17
CaO	1.04	1.30	2.00	1.89	1.12	0.62
MgO	0.15	0.19	0.79	0.64	0.20	0.08
Na_2O	6.91	6.46	6.32	6.54	6.67	4.90
K_2O	5.08	5.44	5.29	4.94	5.62	4.81
Fe_2O_3	5.12	6.79	6.64	8.11	6.15	3.19
MnO	0.12	0.26	0.27	0.32	0.22	0.11
TiO_2	0.33	0.47	0.89	0.79	0.36	0.18
P_2O_5	0.04	0.13	0.37	0.30	0.03	0.01
Total	99.41	99.66	99.19	99.19	99.87	99.31

Table 6. Syenitoid data from Hunter (1925) and Hedlund and Olson (1981). Values for major element oxides are reported in weight percent.

	Hunter (1925)	Syenite data from Hedlund and Olson (1981)		
Sample	Augite syenite	150039	150045	150046
SiO_2	54.99	48.50	53.8	44.7
Al_2O_3	12.98	10.40	11.9	9.2
CaO	5.67	7.20	6.6	9.8
MgO	5.50	10.90	9.2	13.3
Na_2O	2.83	1.30	2.2	1.0
K_2O	7.08	8.40	5.8	4.8
Fe_2O_3	3.13	4.60	3.0	2.1
FeO	3.92	3.30	4.7	6.3
MnO	0.13	0.14	0.14	0.13
TiO_2	0.99	0.81	0.82	1.5
P_2O_5	1.00	1.30	0.66	1.7
H_2O	0.99	0.71	0.56	1.4
CO_2	0	0.68	0.16	1.8
Total	99.21	98.2	99.5	97.7

Table 7. Geochemical data for the country rocks in the Wildcat Gulch study area. Data from Condie and Nuter (1981) and Hedlund and Olson (1981). Values for major element oxides are reported in weight percent. "----" indicates values not reported in the source of the data.

	Mafic and Felsic Dubois Greenstone Samples from Condie and Nuter (1981)							
Sample	B-6	B6A	B-8	B-12	GU-5	GU-6	S-15	B-10
SiO_2	49.4	48.2	48.1	48.8	48.0	50.8	48.5	50.2
Al_2O_3	15.5	14.3	14.9	14.2	14.7	13.8	12.8	12.0
CaO	11.4	12.6	10.6	11.7	13.2	8.88	9.95	8.39
MgO	6.99	6.94	7.13	8.41	6.43	6.37	6.61	6.02
Na_2O	1.86	2.04	2.70	2.39	1.68	3.90	1.21	3.00
K_2O	0.17	0.34	0.61	0.37	0.28	0.37	2.94	1.46
Fe_2O_3	3.55	4.89	4.85	3.40	3.34	3.60	3.32	4.62
FeO	10.20	8.92	8.27	8.36	9.56	10.30	10.80	11.40
MnO	-----	-----	-----	-----	-----	-----	-----	-----
TiO_2	1.25	1.38	1.16	0.97	1.35	1.77	1.56	2.12
P_2O_5	-----	-----	-----	-----	-----	-----	-----	-----
LOI	0.59	0.64	0.65	0.74	0.68	0.63	3.32	0.76
Total	100.9	100.3	99.0	99.3	99.2	100.4	101.0	100.0

	Mafic and Felsic Dubois Greenstone Samples from Condie and Nuter (1981)							
Sample	B-11	A-5	A-6	A-7	FV-1	FV-2	FV-3	FV-8
SiO_2	50.7	49.3	50.4	51.1	76.1	77.5	74.9	69.9
Al_2O_3	13.5	14.1	14.0	14.1	12.7	12.4	13.6	14.6
CaO	7.71	10.30	10.40	9.98	0.13	1.08	1.08	1.11
MgO	5.64	8.66	8.21	7.33	0.27	1.20	0.90	2.04
Na_2O	2.98	3.32	2.85	2.57	3.68	3.16	2.20	0.55
K_2O	1.82	0.21	0.20	1.00	3.60	1.74	3.53	5.77
Fe_2O_3	4.15	4.19	4.97	5.55	1.41	1.73	1.75	2.59
FeO	10.20	7.42	6.47	6.42	1.04	1.27	1.28	1.90
MnO	-----	-----	-----	-----	-----	-----	-----	-----
TiO_2	1.75	0.89	0.96	0.87	0.27	0.26	0.27	0.52
P_2O_5	-----	-----	-----	-----	-----	-----	-----	-----
LOI	0.75	1.54	1.34	1.13	0.97	1.09	0.89	1.55
Total	88.3	91.0	92.0	92.5	98.2	99.1	98.2	97.1

	Mafic and Felsic Dubois Greenstone Samples from Condie and Nuter (1981)					Granite data from Hedlund and Olson (1981)		
Sample	F-1	F-1A	F-8	F-11	SAM	GU-4	100330	150044
SiO_2	77.0	76.6	72.7	72.2	73.0	73.3	73.15	73.2
Al_2O_3	12.9	11.5	13.2	12.7	14.4	14.8	13.45	14.2
CaO	0.29	2.51	1.67	0.88	1.50	1.23	1.86	0.81
MgO	0.12	0.68	1.50	0.21	0.65	0.91	0.57	0.24
Na_2O	2.78	2.51	3.28	1.67	3.77	2.95	3.73	5.6
K_2O	4.93	3.92	3.12	7.49	2.77	3.31	3.43	1.2
Fe_2O_3	1.00	1.06	2.19	2.46	1.36	1.46	1.25	2.5
FeO	0.74	0.78	1.61	1.81	1.01	1.08	1.19	0.85
MnO	-----	-----	-----	-----	-----	-----	0.07	0.02
TiO_2	0.18	0.17	0.36	0.40	0.27	0.27	0.16	0.25
P_2O_5	-----	-----	-----	-----	-----	-----	0.10	0.01
H_2O	-----	-----	-----	-----	-----	-----	0.11	0.62
CO_2	-----	-----	-----	-----	-----	-----	0.21	0.08
LOI	0.91	2.03	1.22	0.82	1.55	0.84	-----	-----
Total	100.9	101.8	100.9	100.6	100.3	100.2	99.3	99.6

may be related to these granite intrusions. Additionally, any correlations that may exist between the Wildcat Gulch syenite and the Dubois Greenstone were evaluated to examine the potential for assimilation processes to have occurred.

Lastly, the Wildcat Gulch syenite samples were compared to the USGS standard nepheline syenite STM-1 (Smith, 1995). This USGS standard nepheline syenite is a peralkaline nepheline syenite from near Eugene, Oregon, and comparisons were made to examine how the Wildcat Gulch syenite would compare to a nepheline syenite in terms of their major and trace element concentrations.

Major Element Results

CIPW Normative Calculation and Classification

CIPW normative calculations were performed to provide a comparison with the mineralogic classification. These calculations were performed using Igpet 2001 software and the data were plotted on a QAP diagram of Le Maitre (2002).

According to the CIPW normative data-based classifications, the monzonite plots as a monzonite, the ferrocarbonatite plots as an alkali-feldspar syenite, the leucocratic quartz monzonite plots as a quartz monzonite, the melanocratic quartz syenite and quartz monzonite plot as syenite and monzonite, the granite of Tolvar Peak and Powderhorn Granite plot as granodiorite and the granite of Cebolla Creek plots as a granite (Table 8; Figure 18).

CIPW normative calculations for the augite syenite of Hunter (1925) and the data of Hedlund and Olson (1981) were also performed. The calculated CIPW normative data were classified on an QAP diagram of Le Maitre (2002) (Figure 18). According to the CIPW normative calculations of the Hedlund and Olson (1981) data, the granite of Tolvar Peak plots as

Table 8. CIPW normative data for the Wildcat Gulch study area rocks.

	Wildcat Gulch Syenite						
	WCG03-01	DUP-WCG03-01	WCG03-04	WCG03-29A	WCG03-31	WCG03-35A	WCG03-36B
Q	5.01	5.03	2.26	0.00	0.43	0.00	0.00
Or	36.11	35.99	42.31	33.51	36.22	23.40	25.41
Ab	28.26	28.35	18.95	20.76	20.39	20.56	16.25
An	13.35	13.28	3.59	6.44	5.13	9.38	10.28
Ne	0.00	0.00	0.00	0.21	0.00	0.00	0.00
Kal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Di	3.59	3.65	12.62	16.45	14.40	22.70	17.05
Hy	4.86	4.84	8.18	0.00	13.01	4.36	0.66
Ol	0.00	0.00	0.00	11.06	0.00	8.50	20.09
Hem	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ap	0.49	0.49	1.97	1.74	1.92	1.02	1.20
CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00
An#	32	32	17	24	20	31	39

	Powderhorn Granite	Granite of Tolvar Peak	Granite of Cebolla Creek	Ferrocarbonatite	Monzonite
	WCG03-40B	WCG03-19	WCG03-36A	WCG03-22	WCG03-26
Q	39.60	42.56	23.13	0.00	2.44
Or	2.90	16.01	25.82	0.00	40.83
Ab	35.37	32.07	33.59	0.00	47.64
An	14.77	1.74	8.55	0.63	0.10
Ne	0.00	0.00	0.00	0.64	0.00
Kal	0.00	0.00	0.00	16.22	0.00
Di	1.97	0.00	0.00	0.00	0.00
Hy	0.33	0.47	3.21	0.00	0.10
Ol	0.00	0.00	0.00	-8.83	0.00
Hem	1.41	0.21	1.14	5.29	1.39
Ap	0.07	0.07	0.42	0.09	0.07
CS	0.00	0.00	0.00	47.08	0.00
An#	30	5	20	100	0

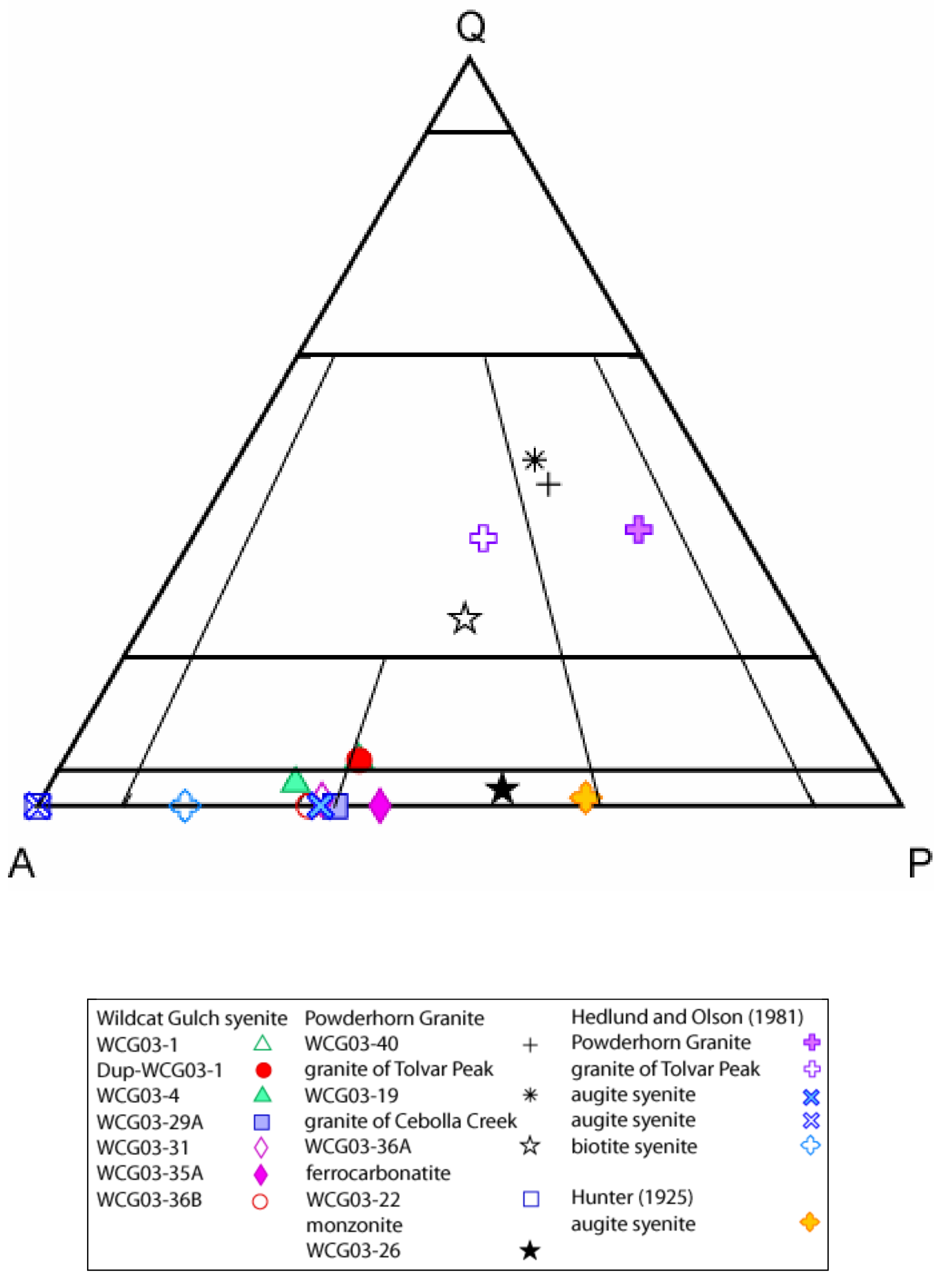


Figure 18. QAP diagram (Le Maitre, 2002) based on CIPW normative calculations for the Wildcat Gulch samples, the augite syenite of Hunter (1925), and for the samples of Hedlund and Olson (1981).

a granodiorite, the Powderhorn Granite plots as a granite, the syenite samples of Hedlund and Olson (1981) plot as syenite and alkali-feldspar syenite. The augite syenite of Hunter (1925) plots as a monzonite. These classifications are similar to the classifications of the syenitoid and granitoid samples of this study with the exception of one syenite of Hedlund and Olson (1981) that plots as an alkali-feldspar syenite.

In comparison to the mineralogical classification, the CIPW calculations contain lower percentages of quartz and plagioclase with respect to the syenitoid and the monzonite samples. Even though the quartz and plagioclase percentages are less in the CIPW normative calculation, the classifications are not that dissimilar.

The Powderhorn Granite and the granite of Tolvar Peak also contain higher quartz and plagioclase percentages in the CIPW normative calculation. According to the CIPW normative calculation, the Powderhorn Granite and the granite of Tolvar Peak plot as granodiorite, while these granite samples fall into the granite field based on their mineralogy.
These differences between the CIPW normative calculation and the modal analysis data are likely the result of the error associated in performing a 100 point count modal analysis.

Geochemical Classification of the Wildcat Gulch Samples

The Wildcat Gulch syenite, granitoid, ferrocarbonatite, and monzonite samples, as well as the Dubois Greenstone, Hunter (1925), and Hedlund and Olson (1981) samples, were all plotted on TAS diagrams for classification based on their geochemistry. In addition, these samples were plotted on AFM diagrams to determine calc-alkaline versus tholeiitic character. In Figure 19, the syenitoid and the granitoid samples of all studies plot within the calc-alkaline trend while the ferrocarbonatite is tholeiitic. The Dubois Greenstone data of Condie and Nuter

a.

b.

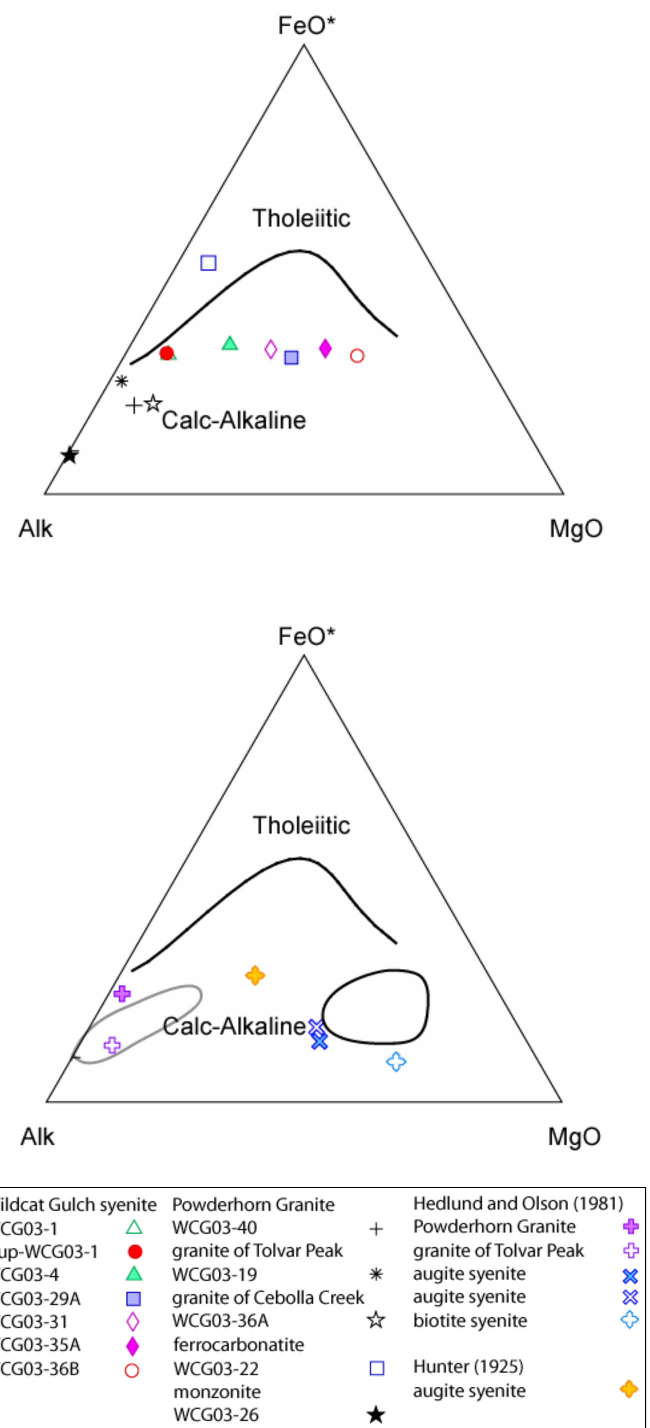


Figure 19. AFM diagrams for the: a) Wildcat Gulch samples, b) data from Hunter (1925) and Hedlund and Olson (1981), as well as fields for the mafic (black) and felsic (light gray) lithodemes of the Dubois Greenstone from Condie and Nuter (1981). Alk = $Na_2O + K_2O$; FeO* = 0.899 * Fe_2O_3; MgO = MgO.

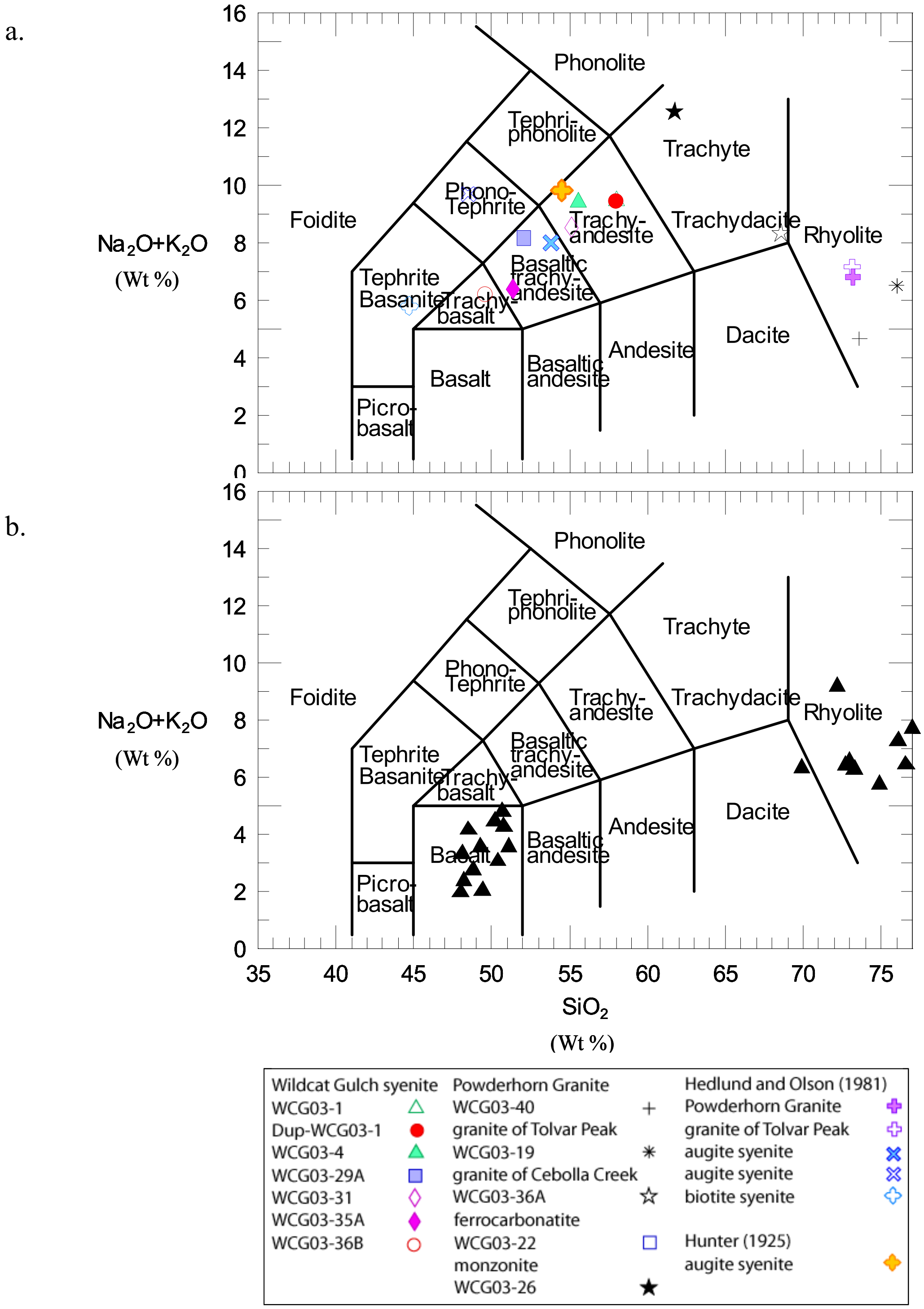


Figure 20. Le Bas et al. (1986) total alkali to silica (TAS) plot for the: a) Wildcat Gulch samples, augite syenite of Hunter (1925), and samples of Hedlund and Olson (1981), and b) rocks of the Dubois Greenstone from Condie and Nuter (1981).

(1981) plots as calc-alkaline. Essentially, all the rocks in the area are silica saturated, and have either abundant Fe in the case of the ferrocarbonatite, or abundant alkalis in the case of the syenitoid, granitoid, and Dubois Greenstone.

On the TAS diagram in Figure 20, the Wildcat Gulch syenite fall in a range that include trachy-basalt, basaltic trachy-andesite, and trachy-andesite. WCG 03-36 (Olson et al., 1977; site A) plots as the most mafic syenitoid, while WCG 03-01 plots as the most felsic syenitoid as a trachy-andesite. Two of the samples of Hedlund and Olson (1981) do not plot in the same fields to the Wildcat Gulch syenite. These two samples plot as a tephrite basanite and a phono-tephrite. The augite syenite of Hunter (1925) plots as a trachy-andesite. The Powderhorn Granite and granite of Tolvar Peak samples of both studies plot as rhyolite. The granite of Cebolla Creek plots as a trachy-dacite. The monzonite plots as a trachyte and the ferrocarbonatite does not plot on the diagram due to its low SiO_2 content.

The mafic lithodeme of the Dubois Greenstone all plot within the basalt field, while the felsic lithodeme fall into the rhyolite and dacite fields.

The geochemical data were also plotted on a TAS diagram modified from Wilson (1989) (Figure 21). On this graph, the syenitoid samples plot in a range that includes gabbro, syeno-diorite, and syenite. The granite of Tolvar Peak and Powderhorn Granite of both studies along with the granite of Cebolla Creek all plot within the granite field. The monzonite plots as a syenite and the ferrocarbonatite does not plot on the diagram due to the low SiO_2 content.

Wildcat Gulch Syenite

The syenitoid intrusions can be separated into two types based upon the QAP CIPW normative results. The leucocratic syenitoid samples are quartz monzonite based upon QAP

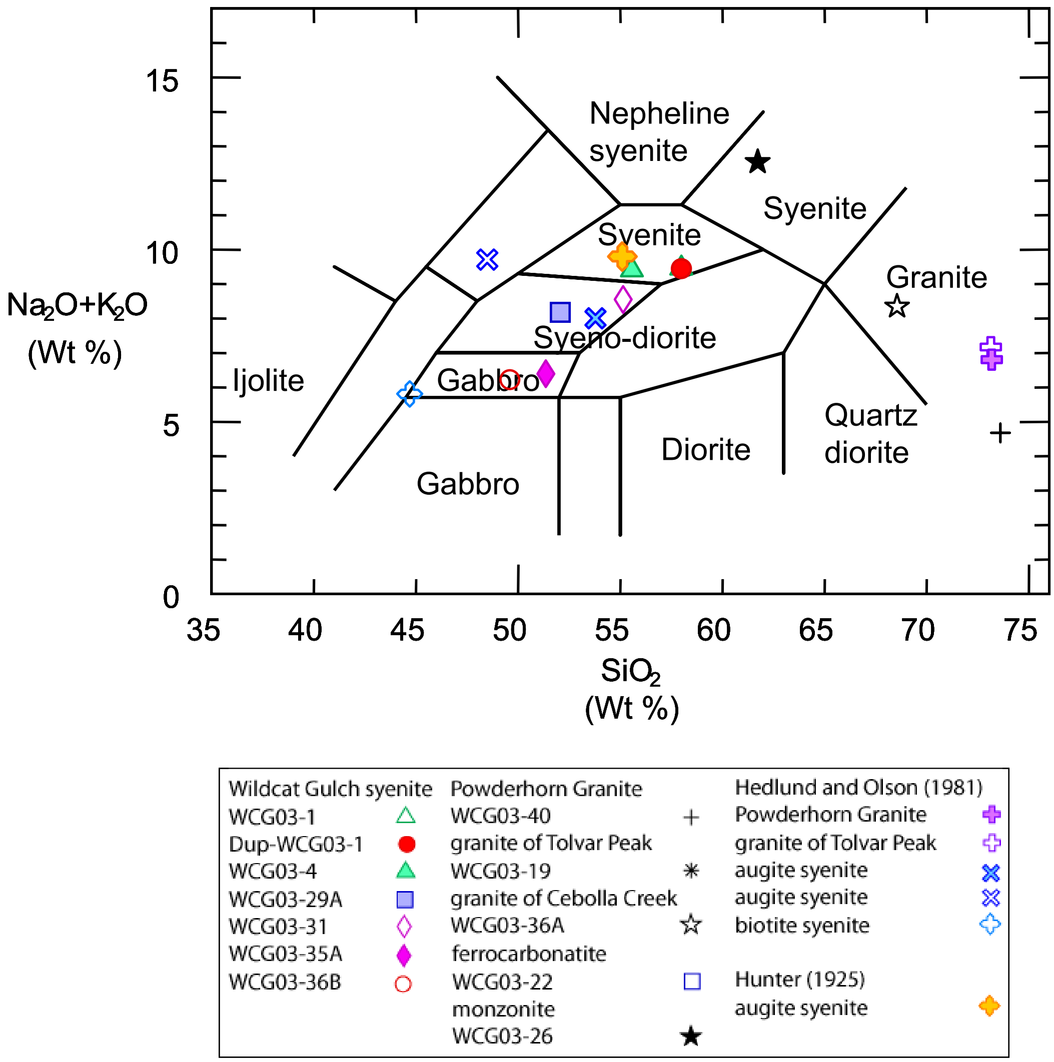


Figure 21. Plot of total alkali to silica (TAS) modified from Wilson (1989) for the Wildcat Gulch study area rocks.

classification by the use of geochemical data while the melanocratic syenitoid samples range from syenite to monzonite based on their geochemical data and the QAP CIPW normative results (Table 8; Figure 18).

Major element data of the syenitoid samples are reported in Table 9. Evaluation of the alkalic nature using the formula $Na_2O + K_2O > 0.3718 \times SiO_2 - 14.5$ of Cappa (1998) reveals that the syenite samples are alkalic because their $Na_2O + K_2O$ values are greater than $> 0.3718 \times SiO_2 - 14.5$. In addition, one of the melanocratic syenitoid samples (WCG 03-04) is ultrapotassic with $K_2O/Na_2O > 3$ (Cappa 1998).

In terms of their major element oxide weight percentages, the percentages of SiO_2, Al_2O_3, CaO, and K_2O suggest that the syenite samples contain an abundance of both K-feldspar and plagioclase (Table 9). In addition, the abundance of MgO and Fe_2O_3 suggest that there is a significant amount of ferromagnesian minerals. The major element chemistry thus reflects the petrology, which contains abundant K-feldspar (microcline), plagioclase, biotite, and riebeckite.

Comparing the major element results of this study with the syenite samples described by Olson et al. (1977) and chemically analyzed in the study of Hedlund and Olson (1981), the data reveals that the major element geochemistry are similar in terms of SiO_2, CaO, K_2O, Na_2O, and Al_2O_3 (Tables 6 and 9). They are also equivalent to the augite syenite of Hunter (1925) and the group of syenite samples from the studies of Sorenson (1974), McLemore and McKee (1989) and Beane and Wobus (1999) in these oxide values (Tables 5, 6, and 9).

The Wildcat Gulch syenite samples differ from the samples of Hedlund and Olson (1981) in their MgO, and to a minor extent, Na_2O concentrations. A plot of Na_2O versus MgO (Figure 22) shows that the Wildcat Gulch syenite samples are elevated slightly in terms of their Na_2O and depleted slightly in terms of MgO with respect to the samples of Hedlund and Olson (1981).

Table 9. Wildcat Gulch syenite major and trace element geochemical data. The label "bd" indicates below instrumentation detection. Major element oxide data is reported in weight percent; trace element data is reported in parts per million.

Sample	Quartz monzonite WCG03-01	Quartz monzonite DUP-WCG03-01	Quartz monzonite WCG03-04	Quartz syenite WCG03-29A	Quartz syenite WCG03-31	Quartz monzonite WCG03-35A	Quartz syenite WCG03-36B
SiO_2	58.0	57.99	55.58	52.07	55.15	51.36	49.60
Al_2O_3	17.0	16.97	12.86	12.61	12.48	11.72	11.58
CaO	3.84	3.84	5.04	6.43	5.74	8.18	7.06
MgO	1.27	1.26	3.74	7.11	5.82	8.17	11.48
Na_2O	3.34	3.35	2.24	2.50	2.41	2.43	1.92
K_2O	6.11	6.09	7.16	5.67	6.13	3.96	4.30
Fe_2O_3	5.50	5.52	7.42	7.53	7.71	7.89	8.91
MnO	0.12	0.12	0.11	0.12	0.13	0.13	0.14
TiO_2	0.51	0.51	0.91	0.81	0.92	0.68	0.71
P_2O_5	0.21	0.21	0.85	0.75	0.83	0.44	0.52
Cr_2O_3	<0.01	<0.01	<0.01	0.05	0.03	0.06	0.11
LOI	2.85	3.00	2.20	2.65	0.95	3.70	1.90
Total	98.75	98.86	98.11	98.30	98.30	98.72	98.23
Co	6.70	7.60	19.20	35.60	26.80	38.80	48.60
Ni	<5	<5	17	157	60	109	329
Cu	55	53	52	109	38	38	90
Sn	5	5	3	3	3	3	3
W	5	5	bd	3	4	4	5
Mo	bd	bd	bd	4	2	bd	3
Zn	66	63	94	90	104	76	90
Ga	21	21	19	19	18	17	16
V	96	96	153	180	170	201	189
Rb	221	223	207	217	251	205	257
Sr	1200	1220	1260	1620	1060	682	1050
Y	36.4	36.1	48.8	29.8	36.7	30.5	32.5
Zr	239	248	671	330	364	123	220
Nb	20	20	19	20	21	21	14
Ta	1	1	1	1	1	2	1
Ba	5020	4950	6040	4490	3980	4590	2910
Cs	5.3	5.3	1.6	24.7	27.6	4.4	49.5
La	58.1	56.5	92.7	70.0	59.4	40.7	56.6
Ce	120	117	189	139	136	86	113
Pr	17.0	16.8	26.8	19.3	17.7	12.8	15.9
Nd	70	68	110	77	74	55	67
Sm	14.2	13.7	21.8	14.5	15.6	12.7	14.3
Eu	3.63	3.34	6.17	4.00	4.23	2.65	3.16
Gd	11.1	11.0	17.5	11.3	13.0	10.5	11.2
Tb	1.61	1.53	2.38	1.48	1.83	1.46	1.58
Dy	7.38	7.33	10.50	6.55	8.21	6.98	7.24
Ho	1.40	1.36	1.83	1.12	1.51	1.23	1.26
Er	3.70	3.71	4.70	2.88	3.74	2.91	3.18
Tm	0.50	0.51	0.64	0.40	0.49	0.36	0.45
Yb	3.4	3.2	4.2	2.6	3.3	2.4	2.8
Lu	0.53	0.51	2.36	0.40	0.49	0.38	0.41
Hf	8	7	16	8	10	5	6
U	4.52	4.39	5.08	6.22	5.23	3.53	4.10
Th	21.3	20.6	15.3	16.1	17.3	21.0	20.2
Tl	0.7	0.7	bd	bd	0.8	bd	0.8

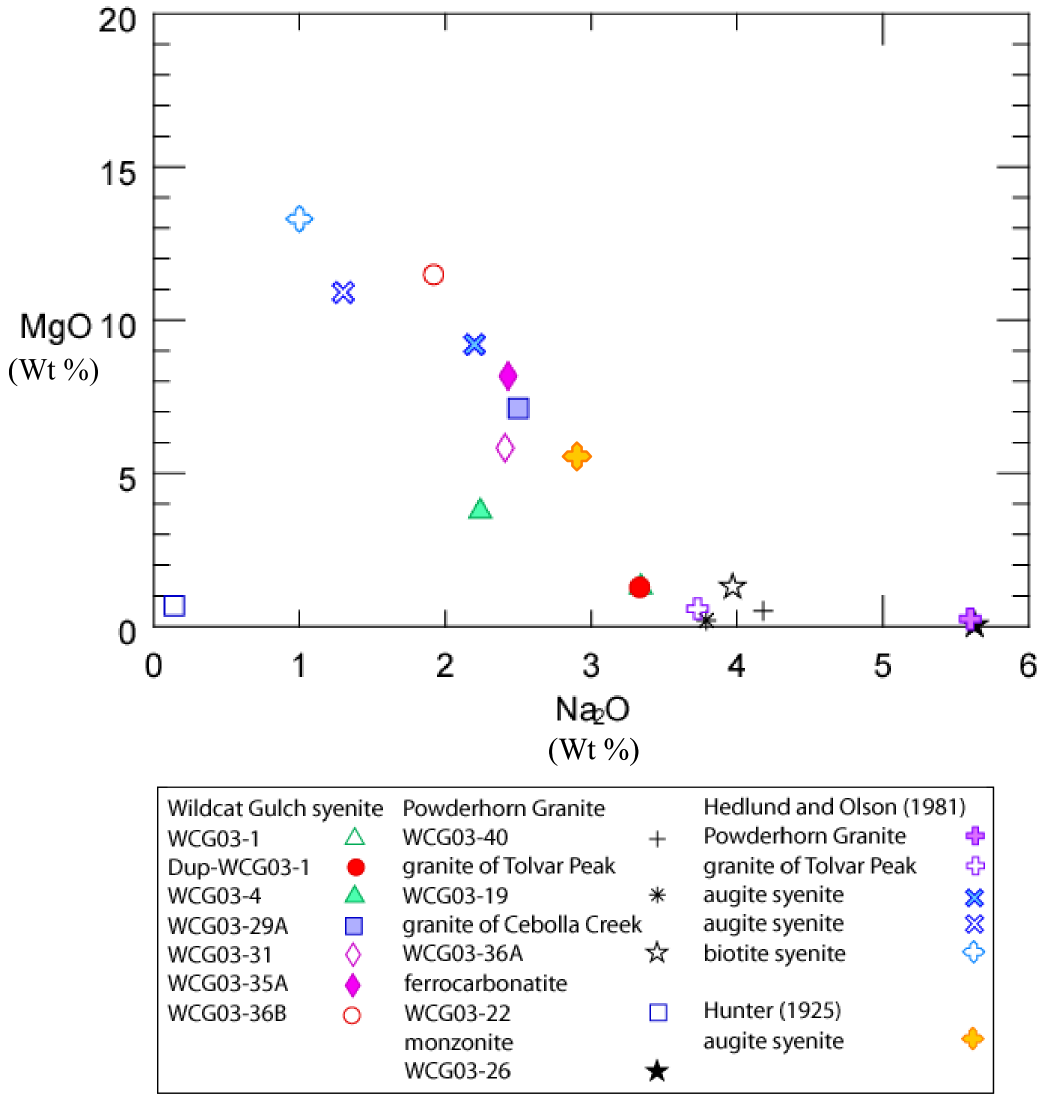


Figure 22. Plot of MgO versus Na_2O for the Wildcat Gulch study area rocks, including the samples of Hunter (1925) and Hedlund and Olson (1981).

This difference may be a result of slight mineralogic variations in the samples. An additional factor may be that the uncertainty of Na_2O is generally the highest (+/- 1 wt %) in the chemical analysis technique.

The Wildcat Gulch syenite display an increase in K_2O, Na_2O, and Al_2O_3 with increase in SiO_2, and a decrease in CaO, MgO, and Fe_2O_3 with an increase of SiO_2 and Al_2O_3 (Figure 23). The high SiO_2 to Al_2O_3 ratio (Figure 24) suggests the presence of sodic pyroxene or sodic amphibole that corresponds with the abundance of sodic amphibole (riebeckite) found in the Wildcat Gulch syenite (Krauskopf, 1967). A Harker diagram of Al_2O_3 versus SiO_2 (Figure 24) also shows a distinction between the leucocratic syenitoid and the melanocratic syenitoid. The Wildcat Gulch syenite samples also plot in a similar field to the augite syenite of Hunter (1925) and control group of syenite samples from Sorenson (1974), McLemore and McKee (1989), and Beane and Wobus (1999). Most of the syenite samples in the control group plot on an opposite trend of the Wildcat Gulch syenite, but the patterns do overlap, and the majority of the major element oxide data are similar (Tables 5, 6 and 9). The Wildcat Gulch syenite samples also closely resemble the geochemistry of the mafic lithodeme of the Dubois Greenstone in terms of their major element oxide concentrations (Table 7; Figures 24, 25, and 26). In Figures 24 and 25, the Wildcat Gulch syenite data plot in similar fields to that of the mafic lithodeme of the Dubois Greenstone in terms of their CaO, Al_2O_3, and SiO_2 concentrations. In Figure 26, the syenite data are elevated in K_2O with respect to the Dubois Greenstone data.

Comparing the Wildcat Gulch syenite data to the USGS standard nepheline syenite STM-1 (Figure 27), the data reveals that the syenitoid have elevated CaO, MgO, TiO_2, and P_2O_5 and depleted Na_2O. The enrichment in CaO and MgO in the Wildcat Gulch syenite samples is most likely to be a result of the abundant riebeckite and plagioclase. The Wildcat Gulch syenite

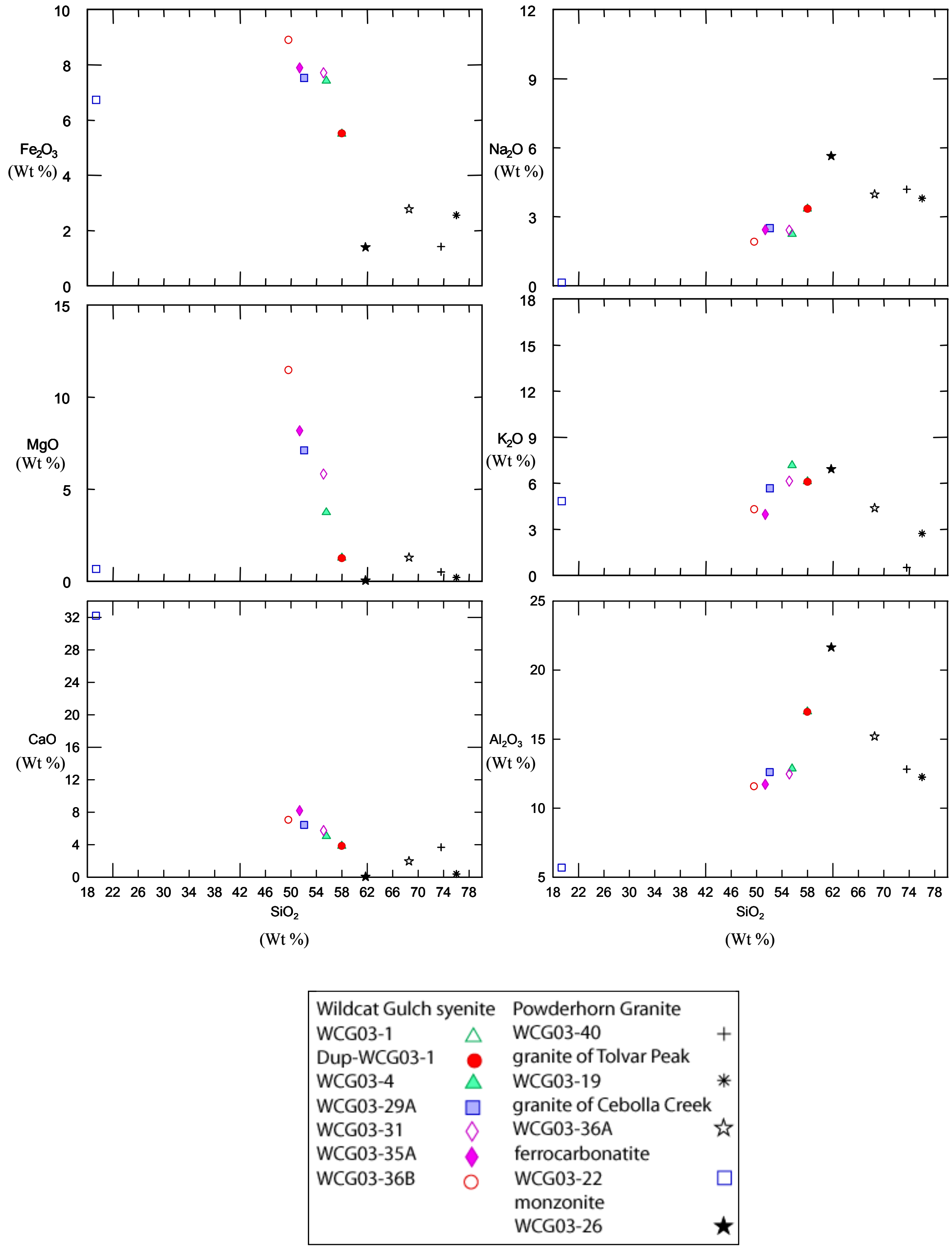


Figure 23. Harker diagrams for the Wildcat Gulch samples.

a.

b.

c.

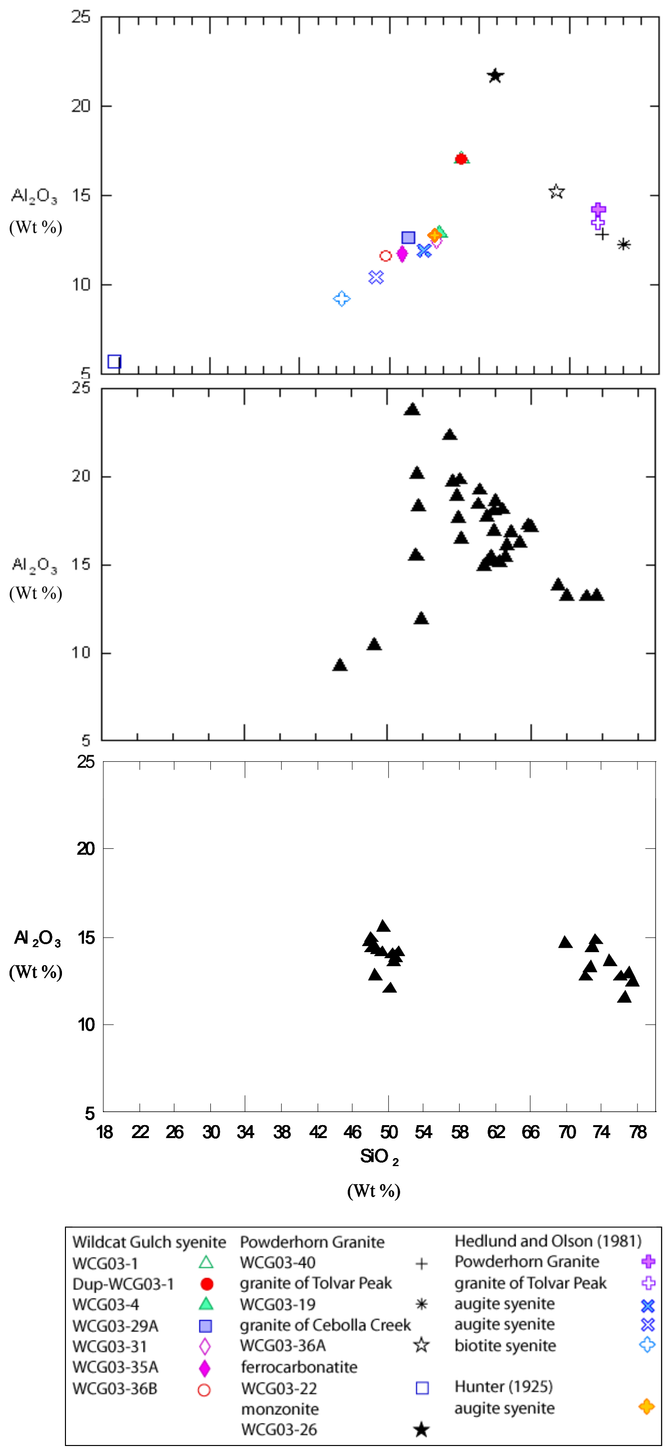


Figure 24. Harker diagram of wt % Al_2O_3 versus wt % SiO_2 for the: a) Wildcat Gulch study area samples, augite syenite of Hunter (1925), and samples of Hedlund and Olson (1981) b) syenite comparison data of Sorenson (1974), McLemore and McKee (1989), and Beane and Wobus (1999), and c) mafic and felsic lithodemes of the Dubois Greenstone from Condie and Nuter (1981).

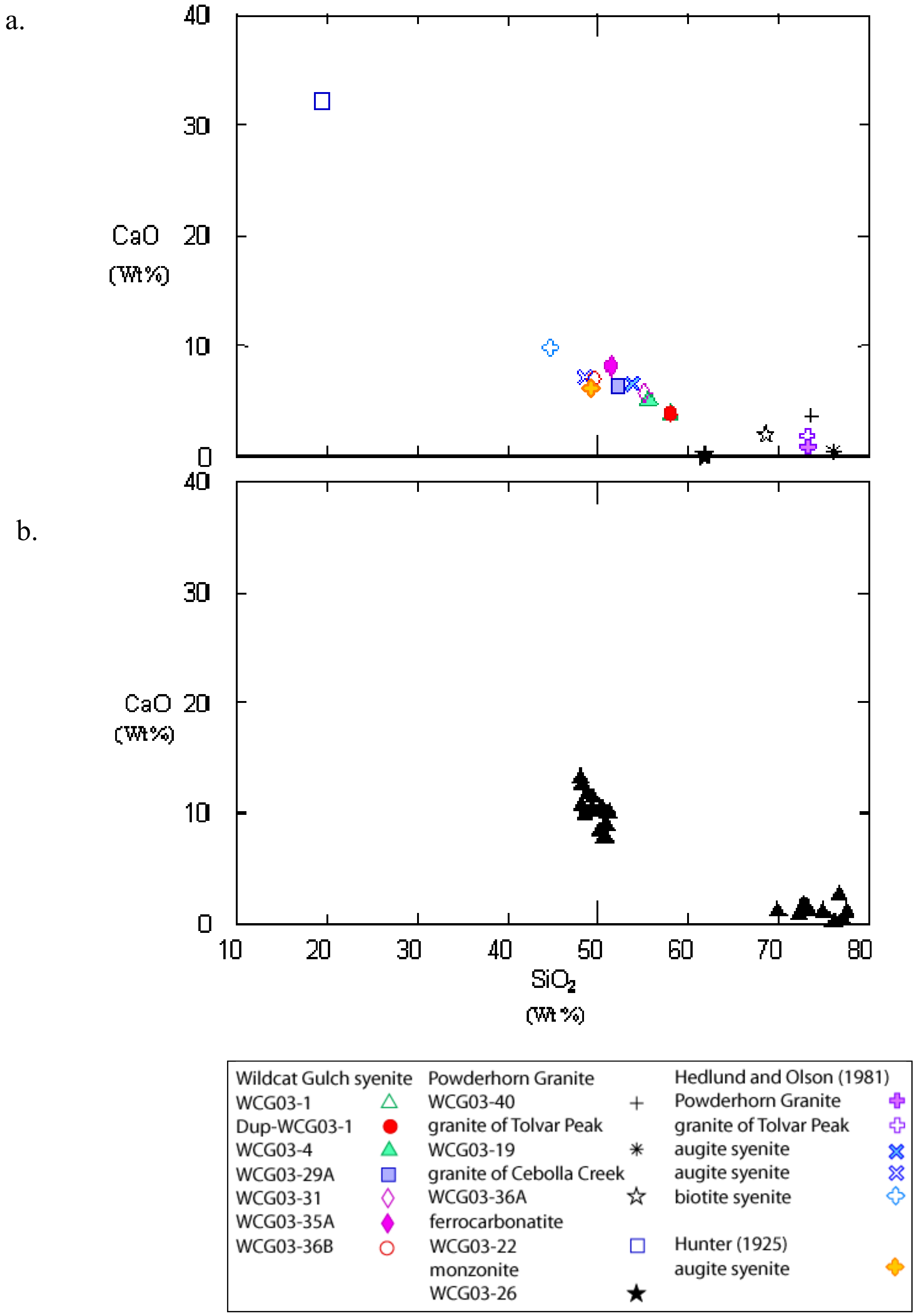


Figure 25. Harker diagram of SiO_2 versus CaO for the: a) Wildcat Gulch samples, augite syenite of Hunter (1925), and samples of Hedlund and Olson (1981) and b) mafic and felsic lithodemes of the Dubois Greenstone from Condie and Nuter (1981).

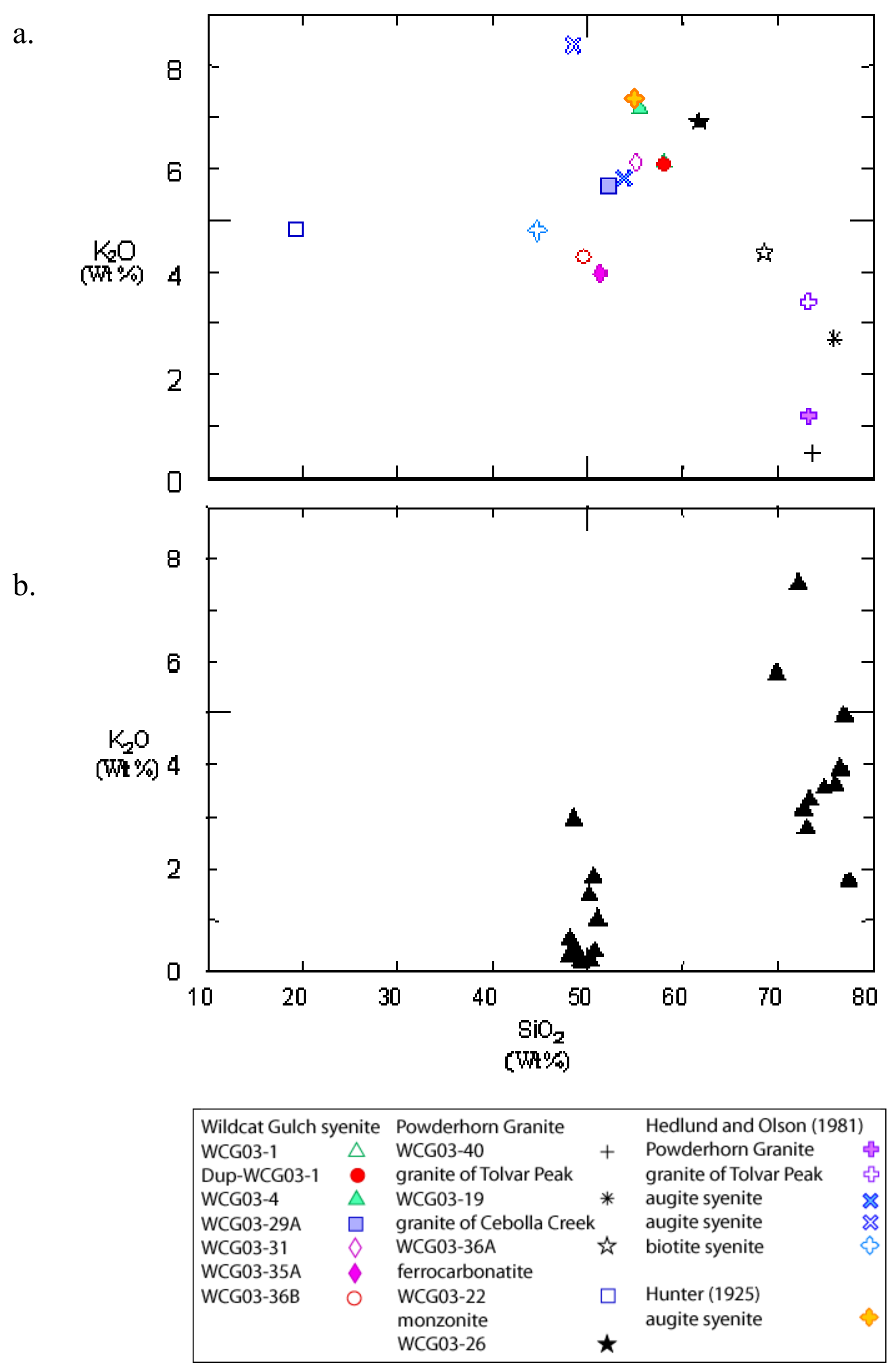


Figure 26. Harker diagram of SiO_2 versus K_2O for the: a) Wildcat Gulch samples, augite syenite of Hunter (1925), and samples of Hedlund and Olson (1981) and b) mafic and felsic lithodemes of the Dubois Greenstone from Condie and Nuter (1981).

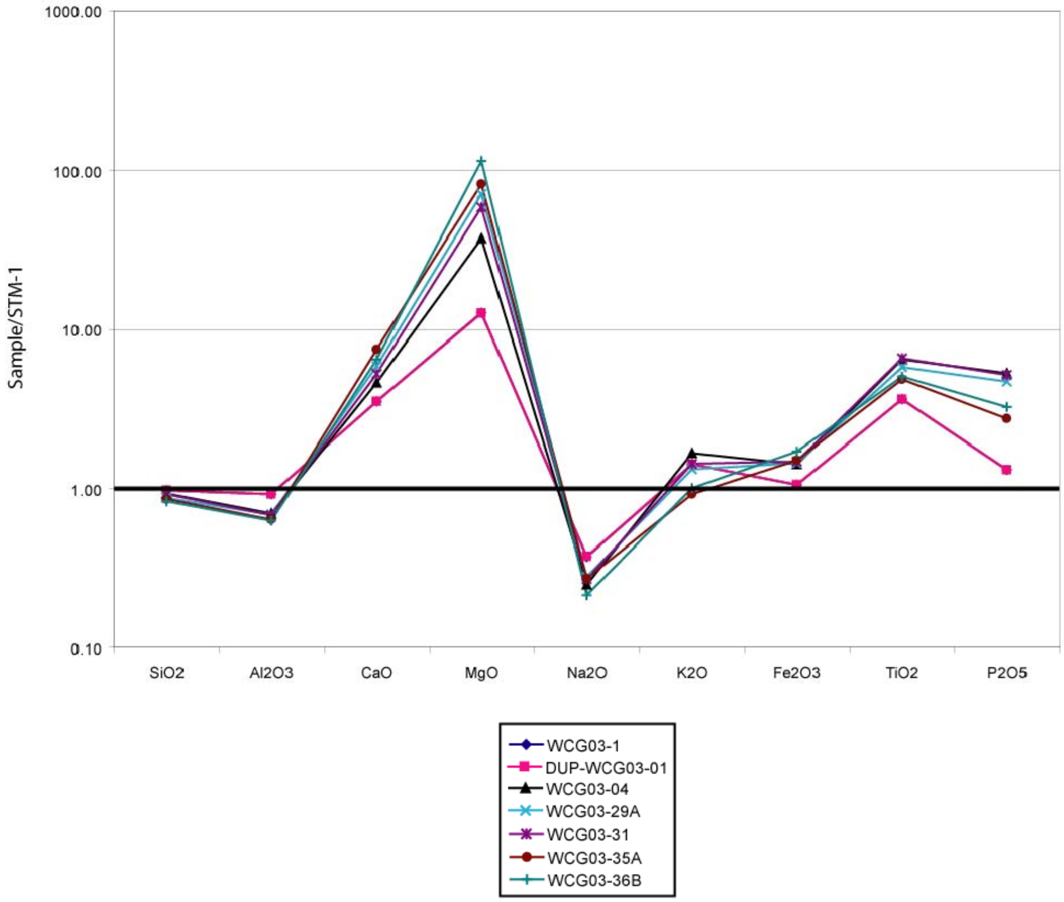


Figure 27. USGS standard syenite STM-1-normalized major element oxide plot of the Wildcat Gulch syenite samples. STM-1 data from Smith (1995).

samples contain abundant plagioclase (up to 40 modal%) and biotite (up to 14 modal %). These mineral percentages could account for the elevated CaO (5 - 9 x STM-1) and MgO (10 - 100 x STM-1).

The elevated P_2O_5 (2 - 8 x STM-1) is a result of the presence of the mineral apatite in the Wildcat Gulch samples, which contain up to 2 modal % apatite.

The depletion of the Wildcat Gulch syenite samples in terms of Na_2O with respect to the STM-1 standard could be a result of the lack of nepheline in the Wildcat Gulch syenite samples. The standard syenite STM-1 is a nepheline syenite, while the Wildcat Gulch syenite samples contain no nepheline or feldspathoids, and would be depleted in Na_2O with respect to a nepheline syenite. Additionally, because there is twice as much Na in nepheline in comparison to riebeckite, the Na_2O values are easily accountable.

The differences in TiO_2 are likely the result of either biotite or rutile because the Wildcat Gulch syenite contain abundant biotite with rutile inclusions.

Granite

The granite of Tolvar Peak and Powderhorn Granite have previously been analyzed for major element geochemistry by Hedlund and Olson (1981) (Table 7; this study). Resampling in this study provided major and trace element geochemistry that is reported in Table 10.

The granite of Tolvar Peak and Powderhorn Granite samples have similar major oxide compositions (Table 10). They differ in terms of their CaO and K_2O oxides. The Powderhorn Granite is enriched in CaO (4 wt %) and depleted in K_2O (<1 wt %) in comparison with the granite of Tolvar Peak, which has less than 1 wt % CaO and 3 wt % K_2O (Table 10). This could simply be a function of the amount of K-feldspar and plagioclase or their mafic phases. The

Table 10. Major and trace element geochemical data for the granite samples of the Wildcat Gulch study area. Major element oxide data is reported in weight percent; trace element data is reported in parts per million.

Sample	Powderhorn Granite WCG03-40B	Granite of Tolvar Peak WCG03-19	Granite of Cebolla Creek WCG03-36A
SiO_2	73.62	76.01	68.56
Al_2O_3	12.82	12.25	15.19
CaO	3.68	0.39	1.96
MgO	0.50	0.19	1.29
Na_2O	4.18	3.79	3.97
K_2O	0.49	2.71	4.37
Fe_2O_3	1.41	2.55	2.77
MnO	0.02	0.02	0.03
TiO_2	0.24	0.17	0.45
P_2O_5	0.03	0.03	0.18
Cr_2O_3	<0.01	<0.01	<0.01
LOI	1.55	0.85	0.95
Total	98.54	98.96	99.72
Co	2.4	1.6	7.6
Ni	<5	<5	29
Cu	12	10	11
Sn	3	<1	2
W	<1	1	6
Mo	<2	2	<2
Zn	18	46	63
Ga	15	18	24
V	9	<5	49
Rb	12.7	63.3	253.0
Sr	393	128	576
Y	31.7	32.6	13.6
Zr	229	195	338
Nb	11	17	24
Ta	1.0	1.3	2.2
Ba	232	885	1740
Cs	2.2	1.6	20.0
La	24.6	28.3	109.0
Ce	49.5	108.0	183.0
Pr	6.69	9.82	21.30
Nd	26.4	38.4	70.8
Sm	6.1	8.4	9.4
Eu	1.14	1.42	2.03
Gd	5.86	6.63	6.42
Tb	1.02	1.16	0.83
Dy	5.85	6.74	3.08
Ho	1.21	1.34	0.49
Er	3.56	4.07	1.25
Tm	0.55	0.61	0.17
Yb	3.8	4.4	1.1
Lu	0.55	0.73	0.15
Hf	7	6	9
U	2.51	2.36	6.62
Th	7.0	7.4	37.7
Tl	<0.5	<0.5	0.7

Powderhorn Granite and granite of Tolvar Peak sampled in this study closely match the samples collected by Hedlund and Olson (1981) with a few minor differences that may be a function of representative samples.

The plot of Al_2O_3 versus SiO_2 (Figure 24), and the data in Tables 7 and 10 of the Powderhorn Granite and granite of Tolvar Peak closely match the rocks of the felsic lithodeme of the Dubois Greenstone, but this may just reflect the overall similarity in the mineralogy.

The granite of Cebolla Creek is mineralogically and chemically classified as a granite. This granite contains approximately 68 wt. % $SiO_{2,}$ which is slightly lower than that of the granite of Tolvar Peak and Powderhorn samples. The granite of Cebolla Creek has similar Al_2O_3, Na_2O, and Fe_2O_3 values to the granite of Tolvar Peak and Powderhorn Granite (Table 9). In terms of MgO oxide, the granite of Cebolla Creek is slightly elevated in relation to the other granite samples. The granite of Cebolla Creek and the granite of Tolvar Peak both have similar K_2O concentrations. The geochemistry of the granite of Cebolla Creek is closer to the geochemical data of the granite of Tolvar Peak and Powderhorn Granite samples than the syenite major element geochemistry.

Ferrocarbonatite and Monzonite

The ferrocarbonatite has low concentrations of Na_2O, Al_2O_3, P_2O_5, and MgO oxides and unusually high concentrations of Fe_2O_3, CaO, TiO_2, and MnO oxides (Table 11). The high Fe_2O_3 and low MgO should be expected given the amount of hematite associated with the ferrocarbonatite.

The monzonite is classified petrographically and geochemically as a monzonite on the classification schemes in Figures 5 and 18. Geochemically, the monzonite has elevated SiO_2 at

Table 11. Major and trace element geochemical data for the ferrocarbonatite and monzonite in the Wildcat Gulch study area. Major element oxide data is reported in weight percent; trace element data is reported in parts per million.

Sample	Ferrocarbonatite WCG03-22	Monzonite WCG03-26
SiO_2	19.36	61.74
Al_2O_3	5.69	21.65
CaO	32.21	0.06
MgO	0.67	0.04
Na_2O	0.14	5.63
K_2O	4.83	6.91
Fe_2O_3	6.73	1.39
MnO	0.36	0.01
TiO_2	3.79	0.26
P_2O_5	0.04	0.03
Cr_2O_3	0.03	<0.01
LOI	26.40	1.00
Total	100.25	98.72
Co	17.5	0.6
Ni	55	<5
Cu	21	7
Sn	<1	3
W	16	4
Mo	6	<2
Zn	110	234
Ga	14	46
V	182	24
Rb	85.5	206.0
Sr	176.0	69.3
Y	49.3	63.7
Zr	51.30	1560.00
Nb	734	415
Ta	24.3	13.7
Ba	495	566
Cs	0.1	0.4
La	57	176
Ce	106	257
Pr	15.0	28.3
Nd	74.0	84.6
Sm	28.6	12.8
Eu	7.44	3.32
Gd	23.1	10.8
Tb	3.13	1.88
Dy	13.4	10.3
Ho	2.14	2.17
Er	4.74	6.46
Tm	0.59	1.00
Yb	3.9	7.0
Lu	0.55	1.03
Hf	<1	33
U	2.73	13.70
Th	25.2	78.7
Tl	<0.5	<0.5

61 wt % in comparison to the syenitoid samples, and is very depleted in CaO and MgO compared to the other rocks in the study (Table 11).

Trace Element Results

This study presents the first trace and rare earth element (REE) analysis of the major intrusive rocks of the Wildcat Gulch study area. All samples were analyzed for their trace and REE concentrations. Using this data, the samples were geochemically classified using a Zr/TiO_2 versus Nb/Y plot of Winchester and Floyd (1977), revised by Pearce (1996) (Figure 28). Figure 28 shows that the syenite samples plot as andesite/basalt or rhyolite/dacite. With the exception of WCG 03-4, which plots as a rhyolite/dacite, this classification agrees with that of the TAS diagrams (Figures 20 and 21). The Powderhorn Granite and granite of Tolvar Peak plot in the rhyolite/dacite field while the granite of Cebolla Creek plots as a trachy-andesite. These classifications are also in agreement with the TAS diagram (Figure 20). The monzonite plots as a phonolite and the ferrocarbonatite plots as a foidite. The monzonite on the TAS diagram plotted as a trachyte, but was in close proximity to the phonolite region. The classifications based on the geochemical data are similar in both the TAS diagrams (Figures 20 and 21) and in the Zr/TiO_2 versus Nb/Y plot (Figure 28).

Two-element discrimination diagrams

Initially, the trace and REE data for all samples were compared through a variety of two-element discrimination diagrams in order to see any similarities or differences in the various lithologies that may aid in the elimination or affirmation of the study hypotheses.

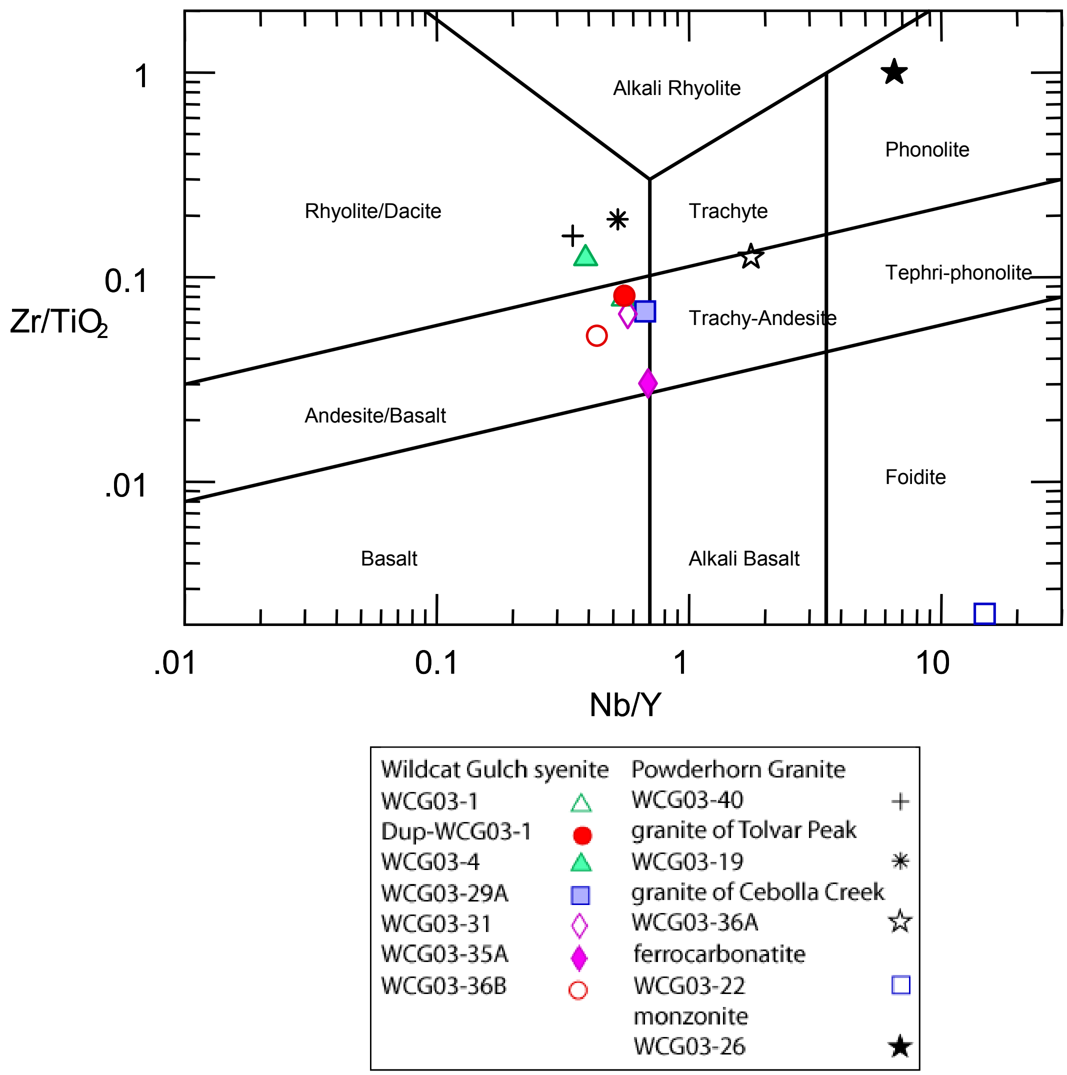


Figure 28. Revised Winchester and Floyd (1977) plot of Zr/TiO_2 versus Nb/Y by Pearce (1996) for the Wildcat Gulch samples.

In a plot of Rb versus Sr (Figure 29), the syenite samples have elevated Rb and Sr with respect to the granite samples of the area with the exception of the granite of Cebolla Creek. The Powderhorn Granite and granite of Tolvar Peak samples contain very low concentrations of Rb and Sr. The ferrocarbonatite plots near the granite of Tolvar Peak, which may be a function of its intrusive nature into the granite or the result of lower percentages of K-feldspar and plagioclase with respect to the syenite samples. The monzonite plots near the syenite in Rb concentration, but has less Sr than the syenitoid. This is unusual considering the amount of plagioclase in the monzonite. It would be expected that the monzonite would have high Sr concentrations given its abundance of plagioclase.

In the U versus Th graph (Figure 30), there are four groupings of samples. The Wildcat Gulch syenite and the ferrocarbonatite samples form a distinct trend of increasing U with decreasing Th. The Powderhorn Granite and granite of Tolvar Peak samples occur together with very low concentrations of U and Th. The granite of Cebolla Creek and the monzonite plot as separate points having elevated U and Th with respect to the surrounding rocks. The monzonite contains the highest concentration of U and Th, which is not surprising because these rocks were considered for Th resources (Olson et al., 1977). It should also be noted that there is no discernable fractionation trend between the granite samples and the syenitoid samples, which may suggest that the syenitoid intrusions are not related to either the Powderhorn Granite or granite of Tolvar Peak.

The plot of Nb versus Ta (Figure 31) shows that the ferrocarbonatite and monzonite are greatly enriched in these elements with respect to the other samples. The syenite and granite samples plot close to the average crustal composition of Nb/Ta ≈12 (Taylor and McLennan,

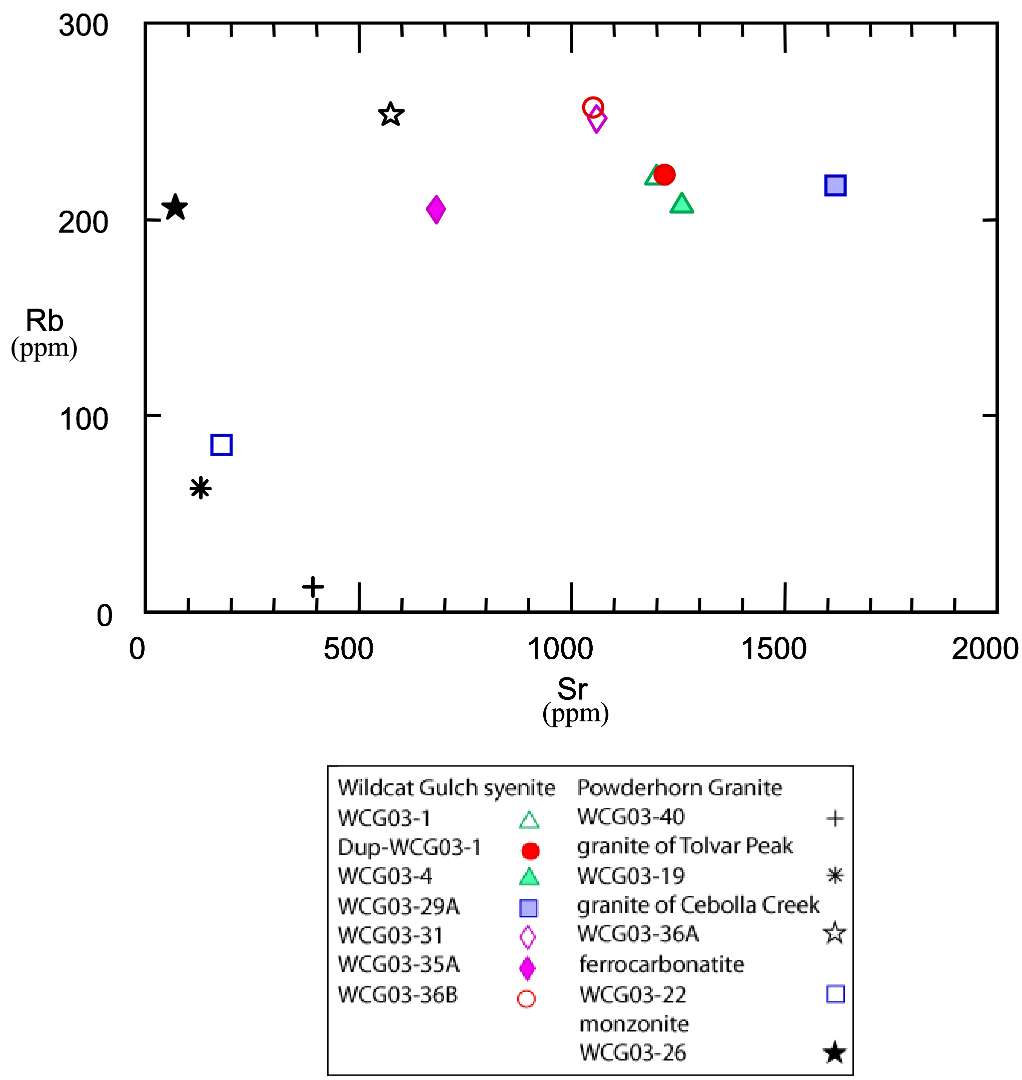


Figure 29. Rb versus Sr trace element plot for the Wildcat Gulch study area samples.

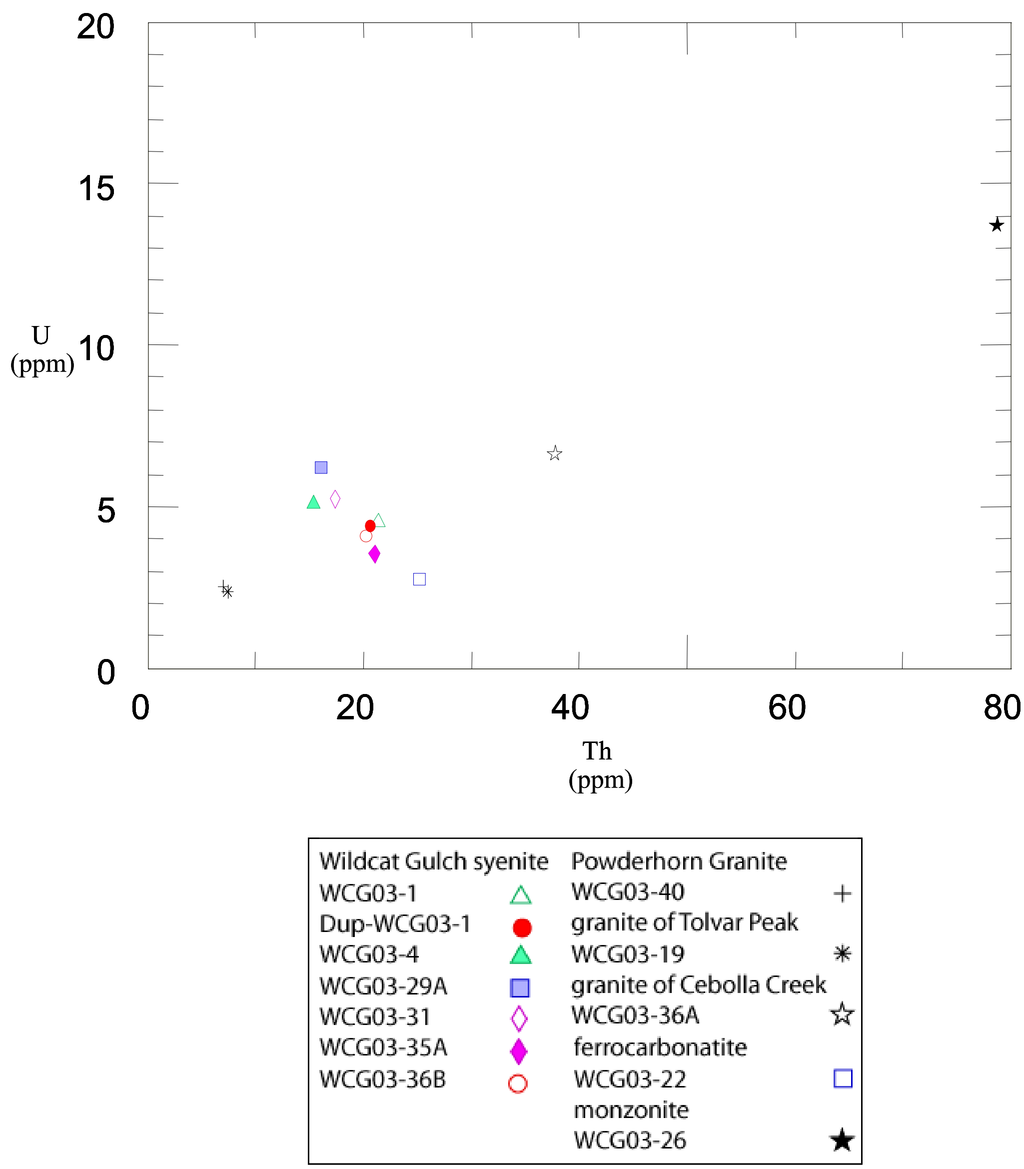


Figure 30. U versus Th trace element plot for the Wildcat Gulch study area rocks.

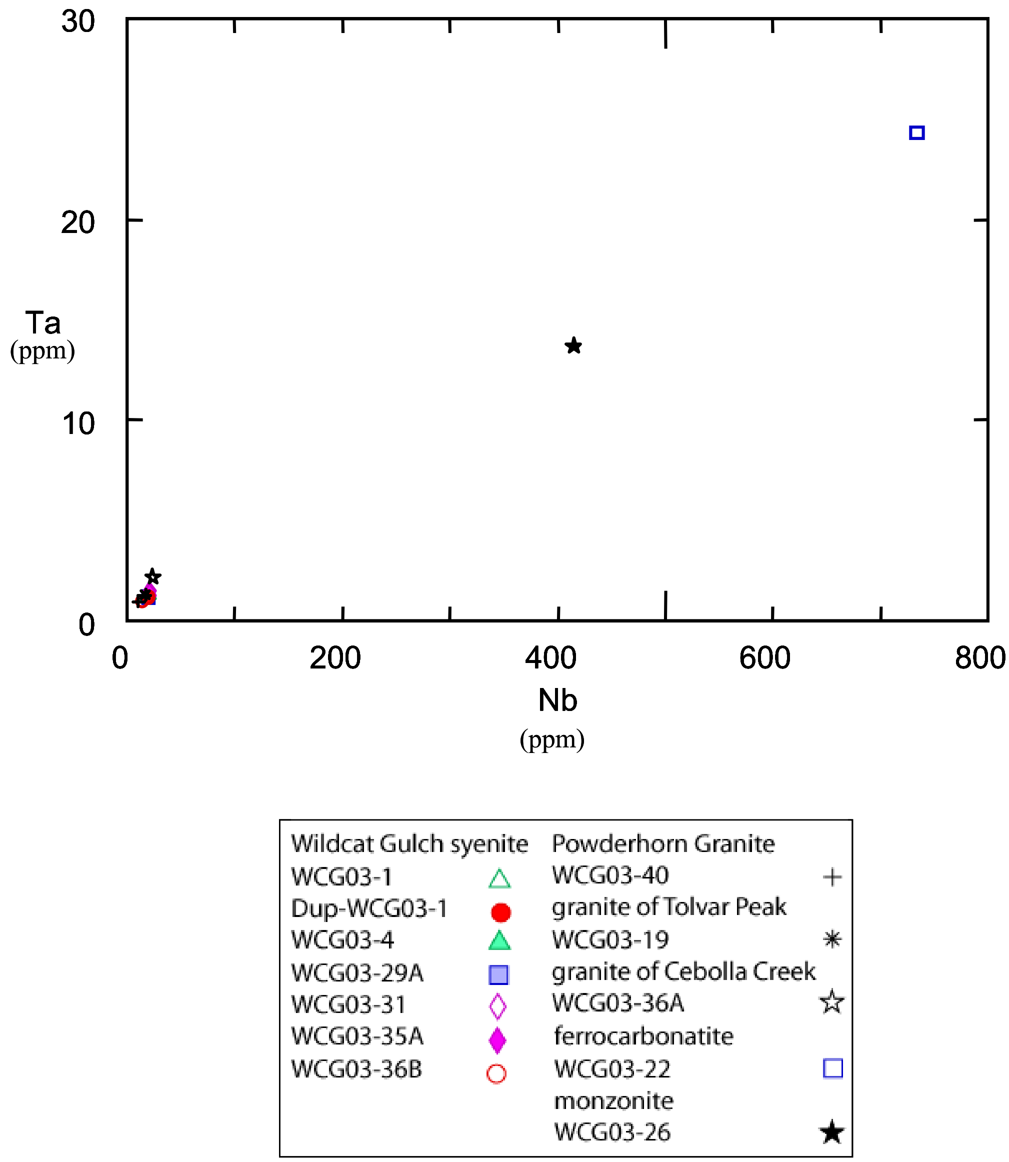


Figure 31. Nb versus Ta trace element plot for the Wildcat Gulch study area rocks.

1985). There is no discernable fractionation trend in this plot between the granite and the syenitoid samples.

The plot of Hf versus Zr (Figure 32) indicates that the syenitoid and the granite samples plot along the average crustal composition line of Zr/Hf $\approx$33 (Taylor and McLennan, 1985), and that all samples plot on a linear trend. There is also no discernable fractionation trend between the granite and the syenitoid in this graph.

In the plot of Sr versus Eu (Figure 33), there is a distinct relationship between the two elements. As the concentration of Eu increases, so does the Sr concentration. This would be expected given that each of these elements can substitute for calcium in plagioclase (Mason, 1966). This is observed in all samples with the exception of the ferrocarbonatite and the monzonite, which have low concentrations of strontium.

The plot of Rb versus K_2O (Figure 34) shows that the syenitoid samples contain elevated Rb and K_2O with respect to the Powderhorn Granite and granite of Tolvar Peak samples. The granite of Cebolla Creek and syenitoid samples have identical amounts of Rb and K_2O. The monzonite has elevated Rb and K_2O amounts that roughly equal the amount of WCG 03-4, which is a melanocratic syenitoid from the northern part of the field area.

The plot of Ba versus K_2O shows (Figure 35) there is an increase in the Ba concentration with an increase in K_2O, with the exception of the monzonite and ferrocarbonatite samples that contain less Ba.

The plot of V versus Fe_2O_3 (Figure 36) shows that since the syenitoid are enriched in the Na- and Fe-rich riebeckite, it is to be expected that these samples would have high concentrations of V and Fe_2O_3. Additionally, there is separation between the melanocratic syenitoid and the leucocratic syenitoid. There is also an enrichment trend from the granite

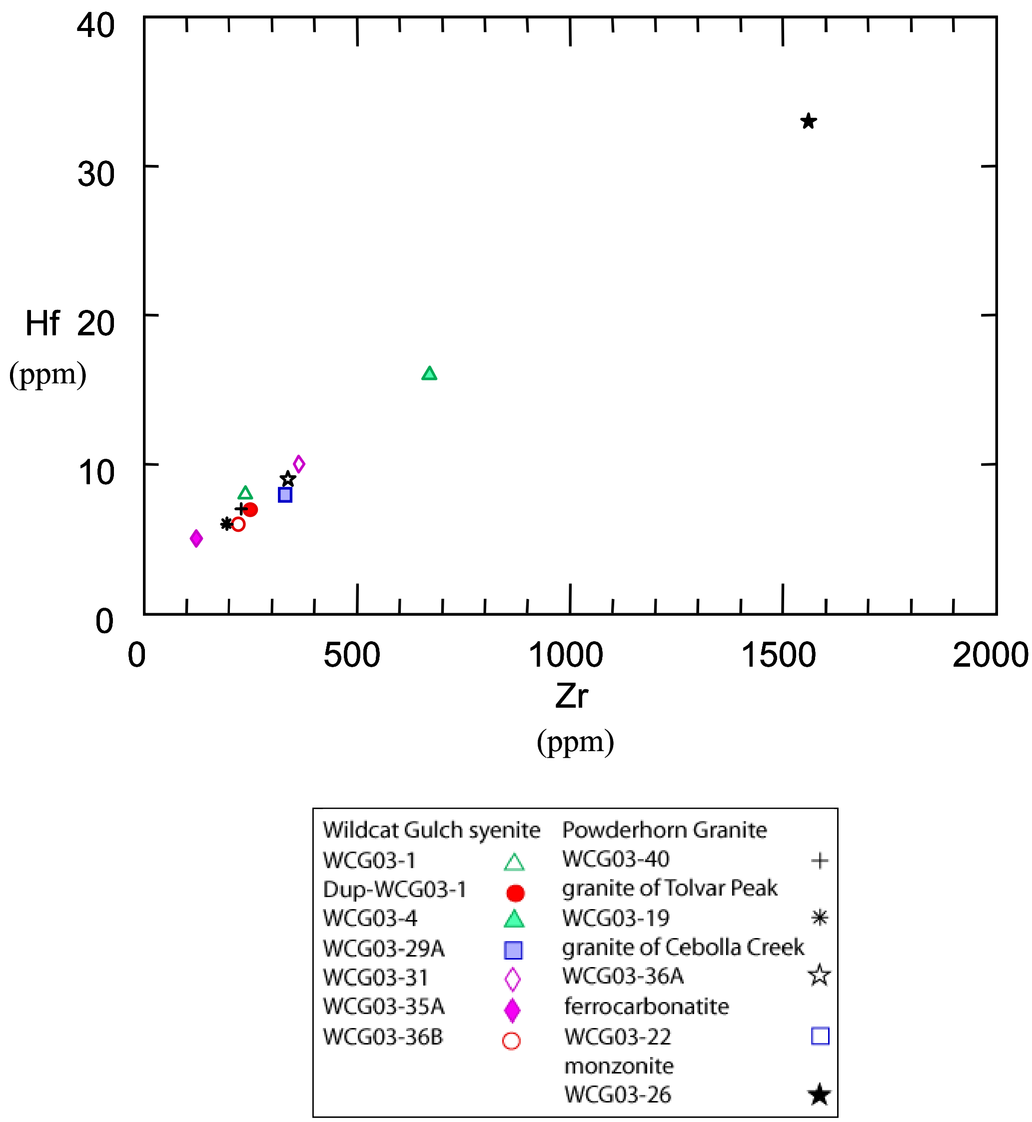


Figure 32. Zr versus Hf trace element plot for the Wildcat Gulch study area rocks.

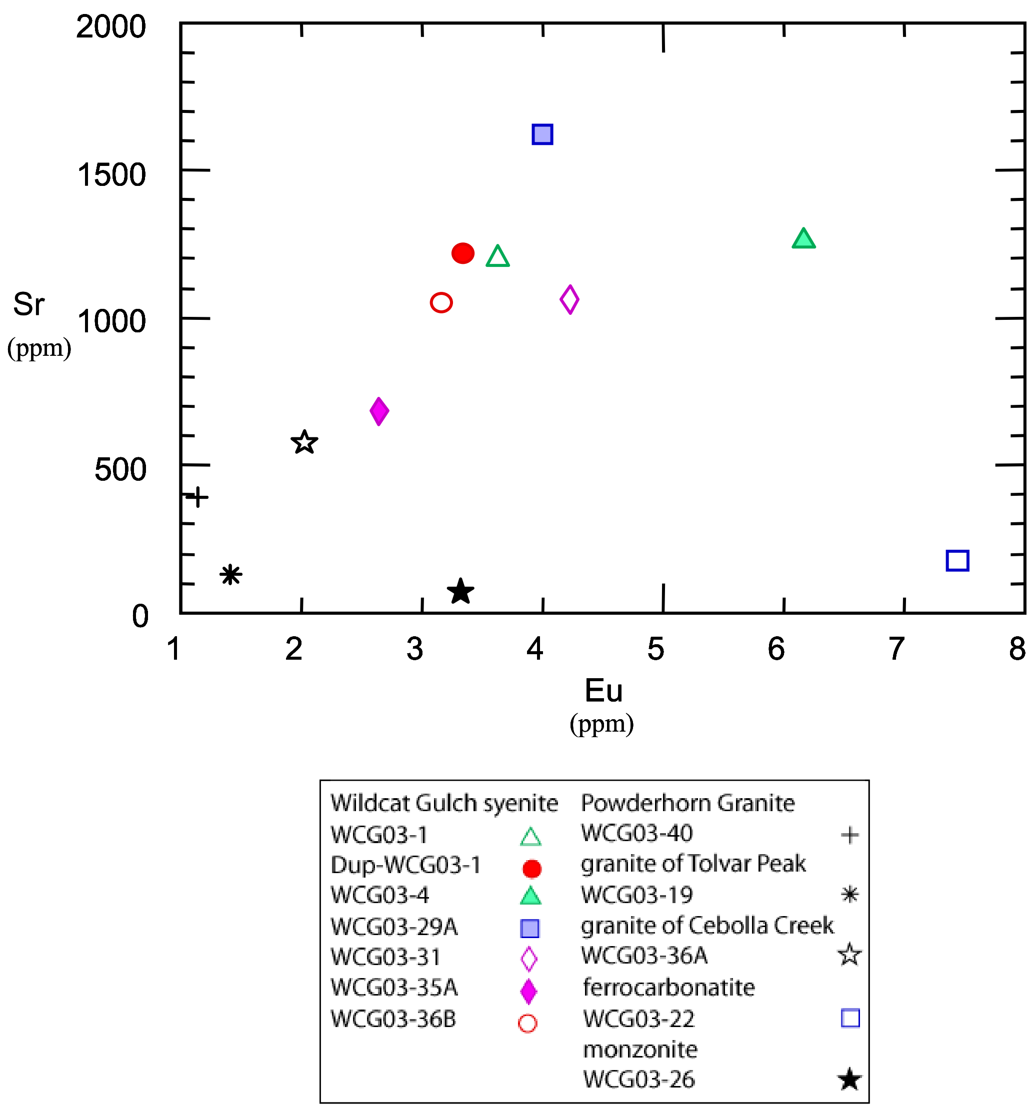


Figure 33. Sr versus Eu trace element plot for the Wildcat Gulch study area rocks.

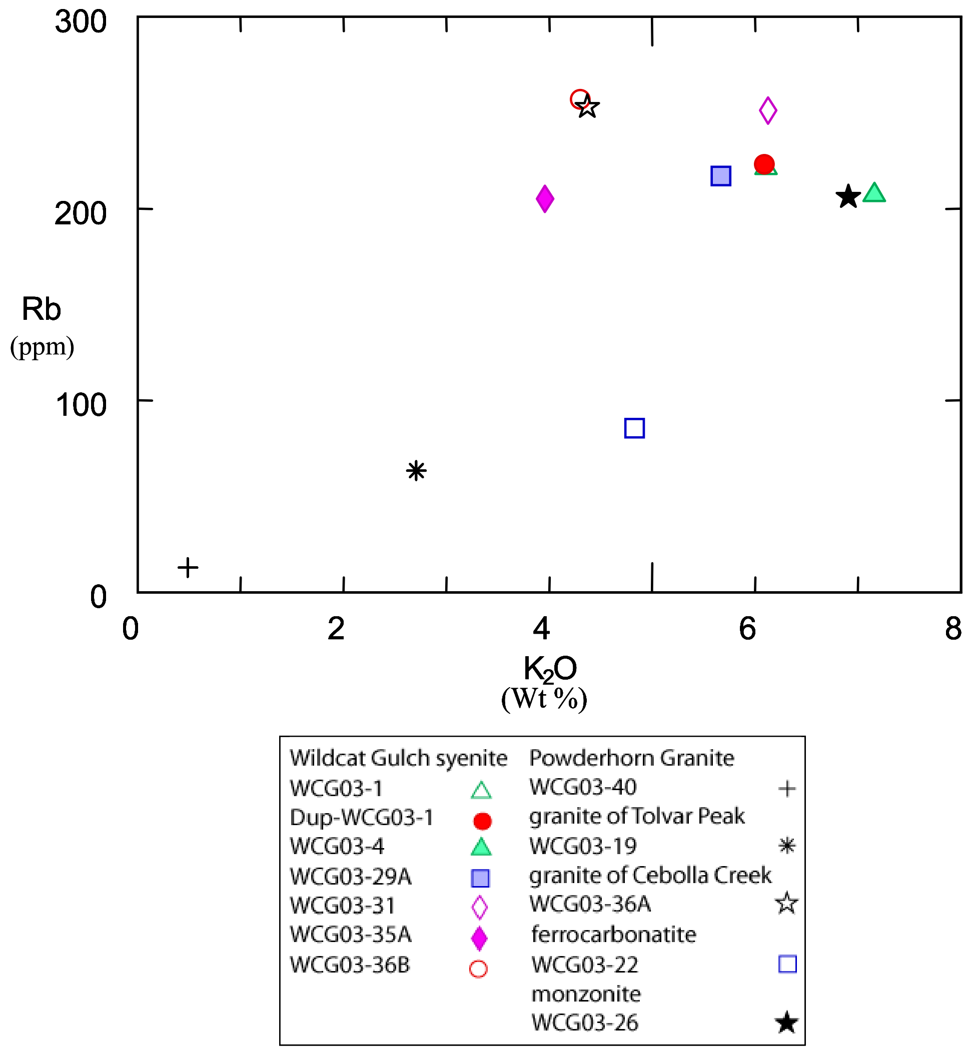


Figure 34. Rb versus wt. % K_2O for the Wildcat Gulch study area rocks.

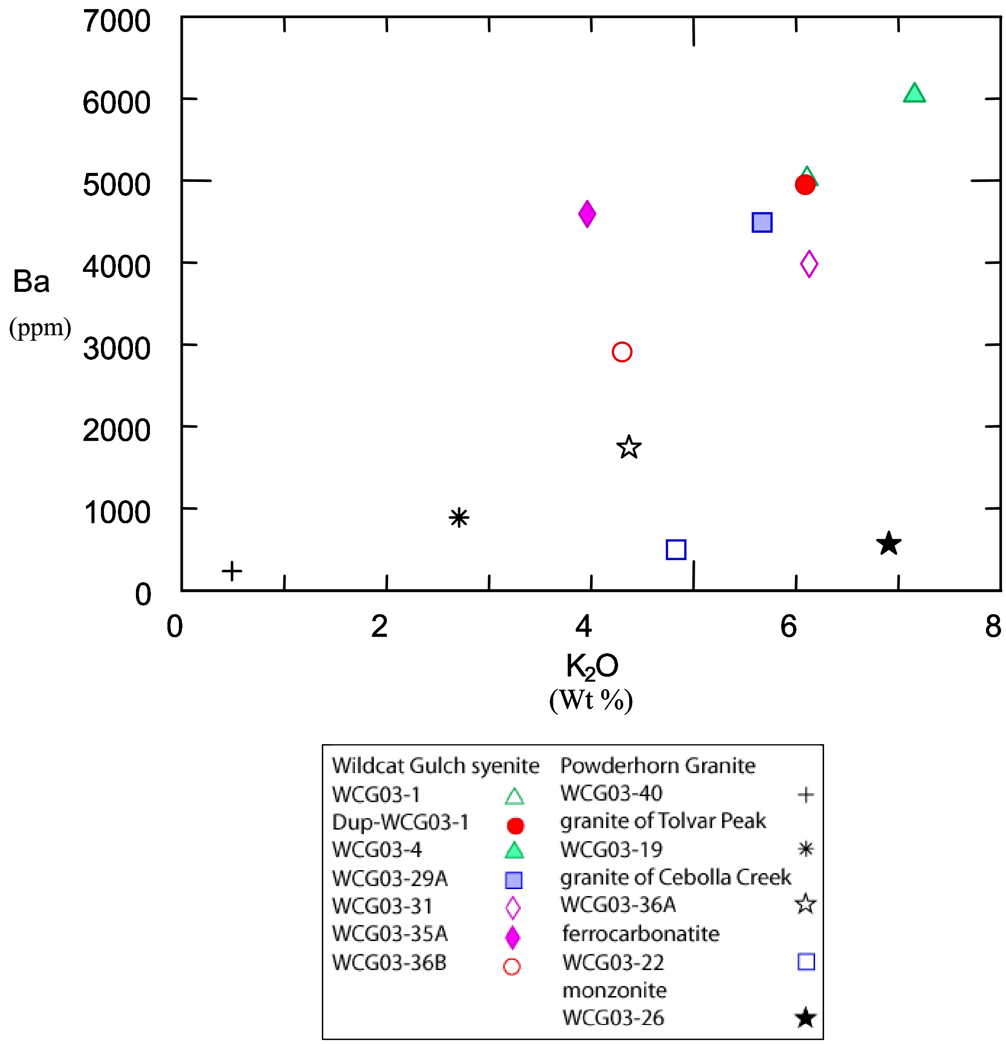


Figure 35. Ba versus wt. % K_2O plot for the Wildcat Gulch study area rocks.

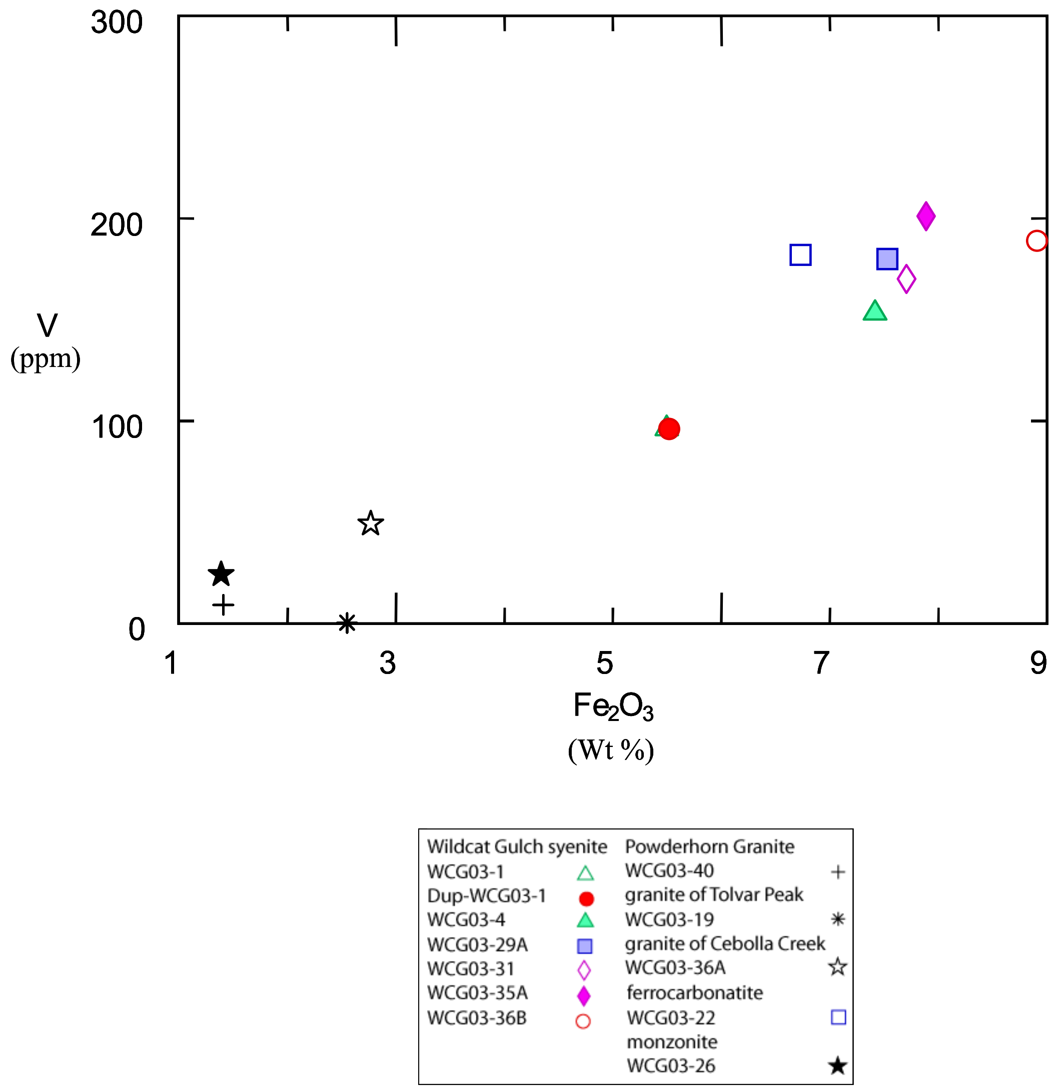


Figure 36. V versus wt. % Fe_2O_3 for the Wildcat Gulch study area rocks.

and monzonite samples, both of which are low in V and Fe_2O_3 to the leucocratic syenitoid, which has moderate concentrations of these components. In addition, the enrichment trend is seen from the leucocratic syenitoid to the melanocratic syenitoid and the ferrocarbonatite that have elevated V and Fe_2O_3 concentrations. This trend may represent a fractionation trend from a single source material, or it may merely be a function of the mineralogy of the various rocks.

The melanocratic syenitoid samples contain elevated concentrations of Cu and Ni observed in Figure 37. The melanocratic syenitoid samples, which are enriched in Ni and Cu, also contain elevated Fe_2O_3 concentrations. This is expected given that Ni and Cu readily substitute for Fe and Mg. Additionally, this mineralization may be related to the Cu mineralization of the area (Cappa, 1998).

Wildcat Gulch Syenite

The Wildcat Gulch syenite were plotted on a chondrite-normalized rare earth element (REE) plot using the normalization of Nakamura (1974). The syenitoid samples have light rare earth elements (LREE) that are elevated 200 - 500 x chondrite (Table 9; Figure 38c). The heavy rare earth elements (HREE) pattern elevated between 10 - 30 x chondrite (Figure 38c). The REE plots show a slight negative Eu anomaly possibly due to loss of plagioclase. The Eu concentrations within the syenite samples is close to average Eu in syenite samples of 2.8 ppm (Siegel, 1974). WCG 03-4 is slightly more elevated in overall REE than the other samples, but has a similar trend.

The Wildcat Gulch syenite data in comparison to the USGS standard nepheline syenite STM-1 of Smith (1995) have similar patterns of LREE enrichment and relatively 1985). There is no discernable fractionation trend in this plot between the granite and the syenitoid samples.

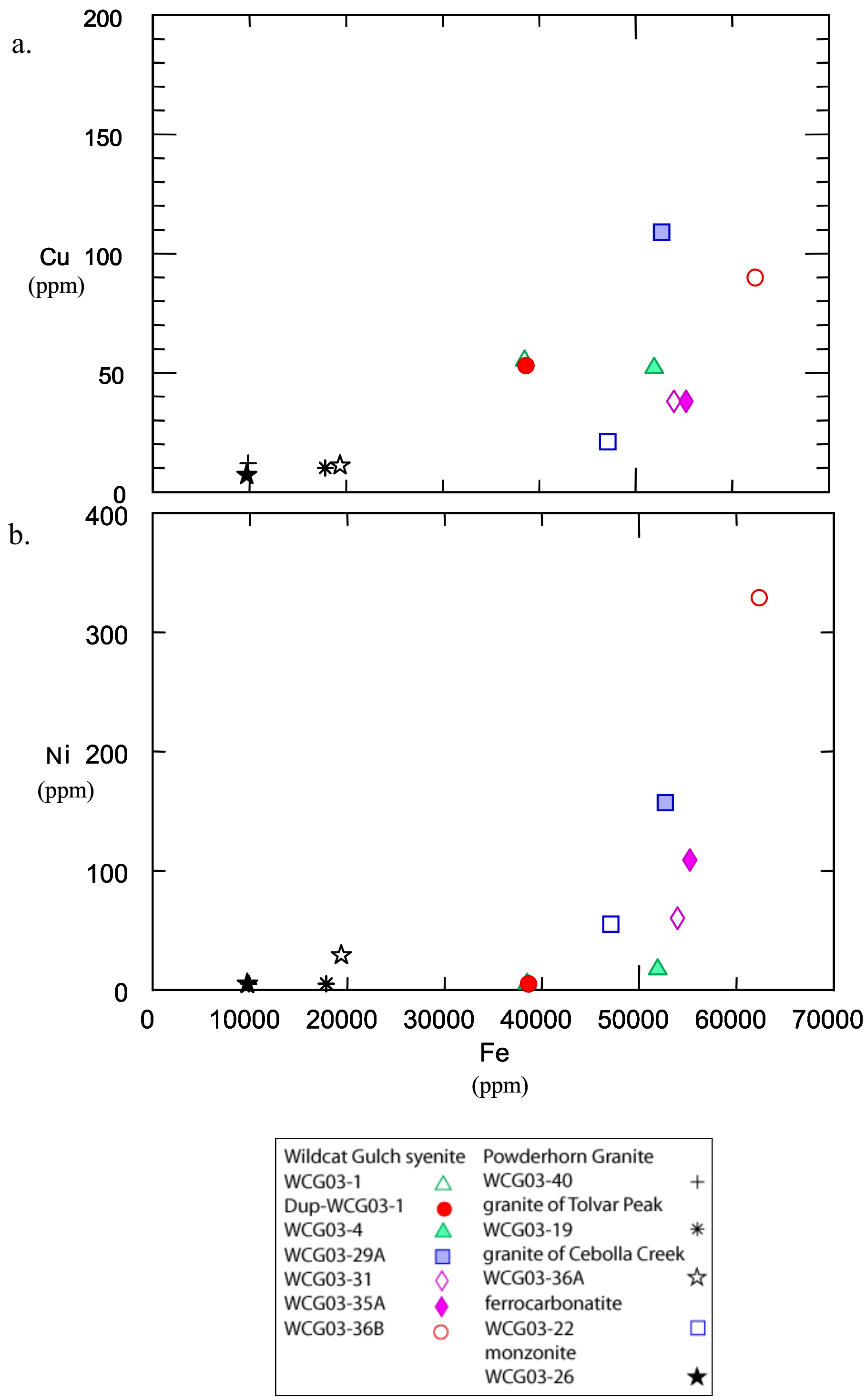


Figure 37. a) Cu versus Fe and b) Ni versus Fe for the Wildcat Gulch samples.

a.

b.

c.

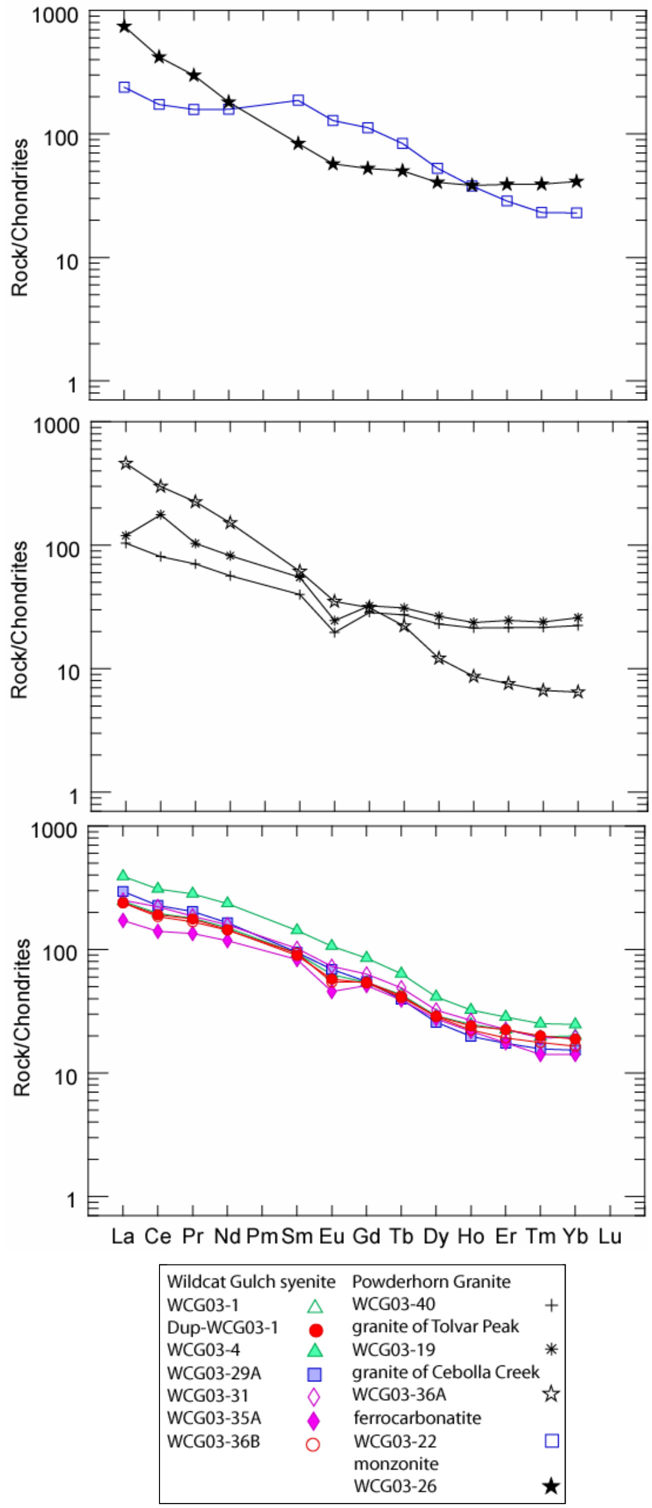


Figure 38. Chondrite-normalized plots of the: a) ferrocarbonatite and monzonite, b) Powderhorn Granite, granite of Tolvar Peak, and granite of Cebolla Creek, and c) Wildcat Gulch syenite. Chondrite normalization values are from Nakamura (1974).

flat HREE (Figure 39). STM-1 differs from the Wildcat Gulch syenite in that it contains a large negative Ce anomaly.

In the N-MORB-normalized trace element plot (Figure 40c) using the normalization values of Sun and McDonough (1989), the syenitoid samples are enriched in the mobile, large ion lithophile (LIL) elements (Cs, Rb and Ba) with respect to the more immobile elements. The syenitoid samples have elevated Ba concentrations between 3000 and 6000 ppm. This result would be expected given these elements readily substitute for K and Na.

The syenitoid samples also contain a variety of Cs concentrations. As Cs can substitute for Ba and K, it is likely that the range in Cs values is a result of variable substitution for these elements (Mason, 1966).

In the N-MORB-normalized plot (Figure 41) there are distinct differences between the Wildcat Gulch syenite and STM-1. STM-1 contains lower concentrations of Ba, Ce, and Ti and higher concentrations of Zr and Nb as compared to the Wildcat Gulch syenite.

A plot of Ba versus Rb versus Sr in Figure 42 shows that K-feldspar is more abundant that plagioclase because Ba readily substitutes for K in K-feldspar. However, it is also possible that the high Ba concentrations may be due to amphibole or biotite because both minerals may be enriched in Ba (Siegel, 1974).

Granite

The Powderhorn Granite, granite of Tolvar Peak, and granite of Cebolla Creek have light rare earth elements (LREE) that are elevated 100 - 500 x chondrite (Table 10; Figure 38b). The heavy rare earth elements (HREE) pattern ranges from 7 - 30 x chondrite and are relatively flat (Figure 38b). The granite of Tolvar Peak and Powderhorn Granite REE patterns that are

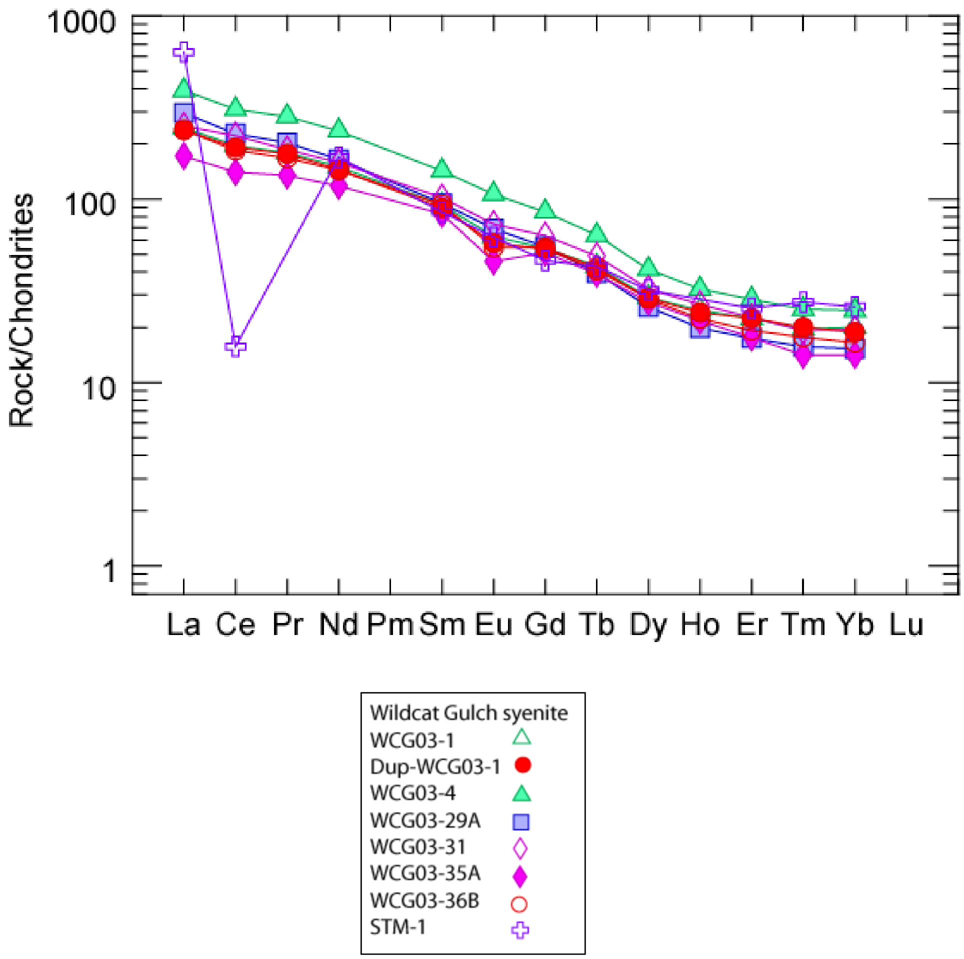


Figure 39. Chondrite-normalized plot of the Wildcat Gulch syenite and USGS standard nepeline syenite STM-1. STM-1 data is from Smith (1995). Chondrite-normalization values are from Nakamura (1974).

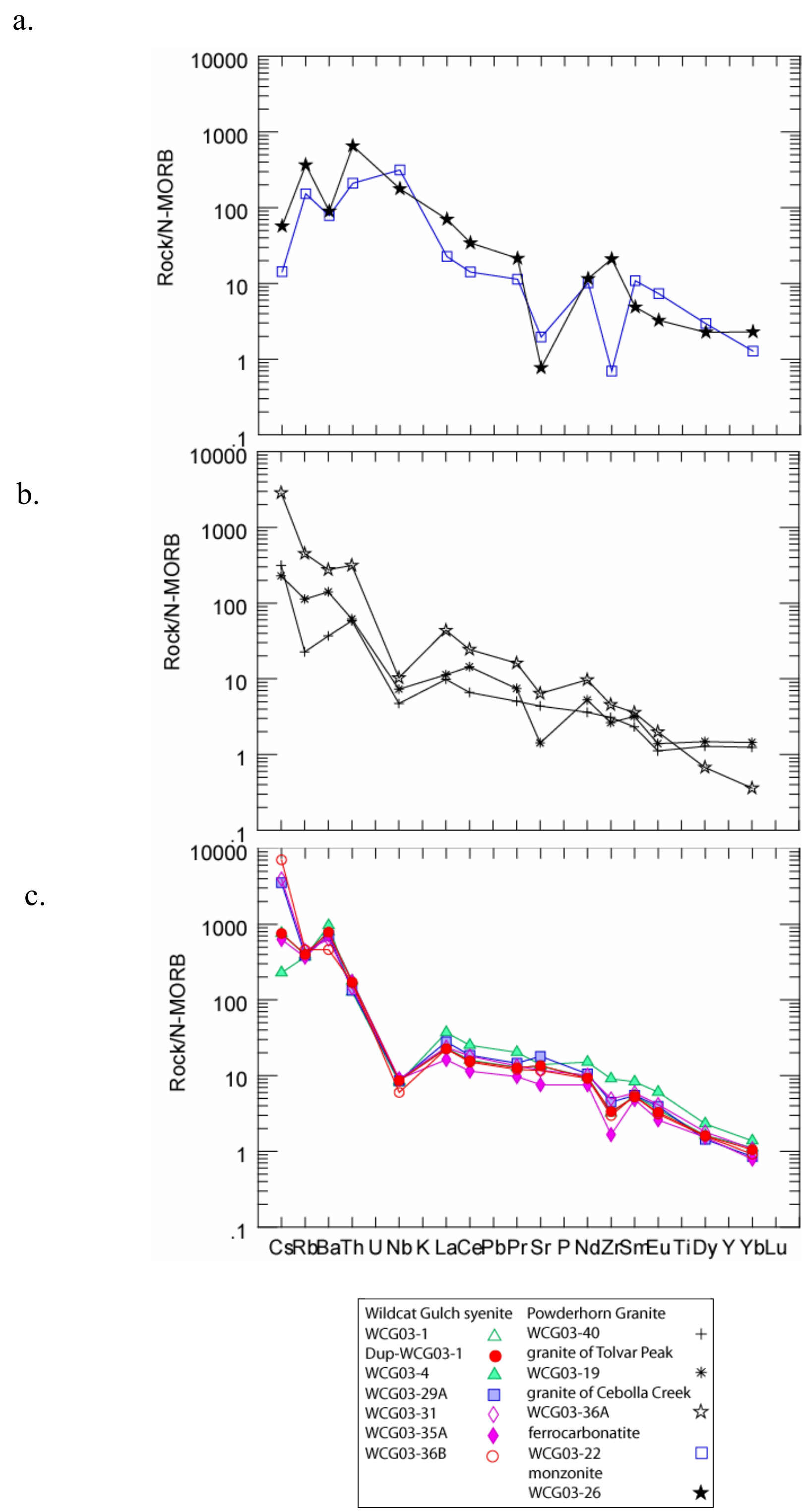


Figure 40. N-MORB-normalized plots for the: a) ferrocarbonatite and monzonite, b) Powderhorn Granite, granite of Tolvar Peak, and granite of Cebolla Creek, and c) Wildcat Gulch syenite. N-MORB-normalization values are from Sun and McDonough (1989).

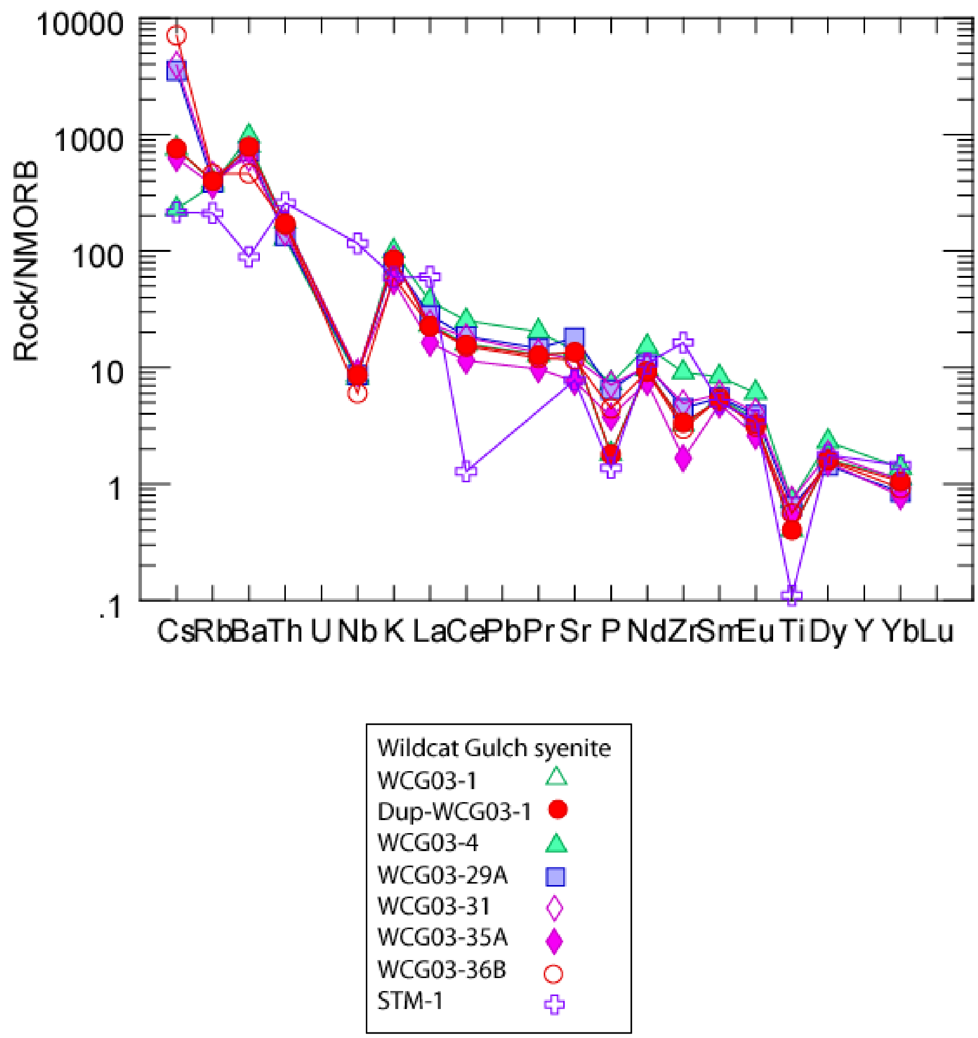


Figure 41. N-MORB-normalized plot of the Wildcat Gulch syenite and USGS standard nepeline syenite STM-1. STM-1 data is from Smith (1995). N-MORB-normalization values are from Sun and McDonough (1989).

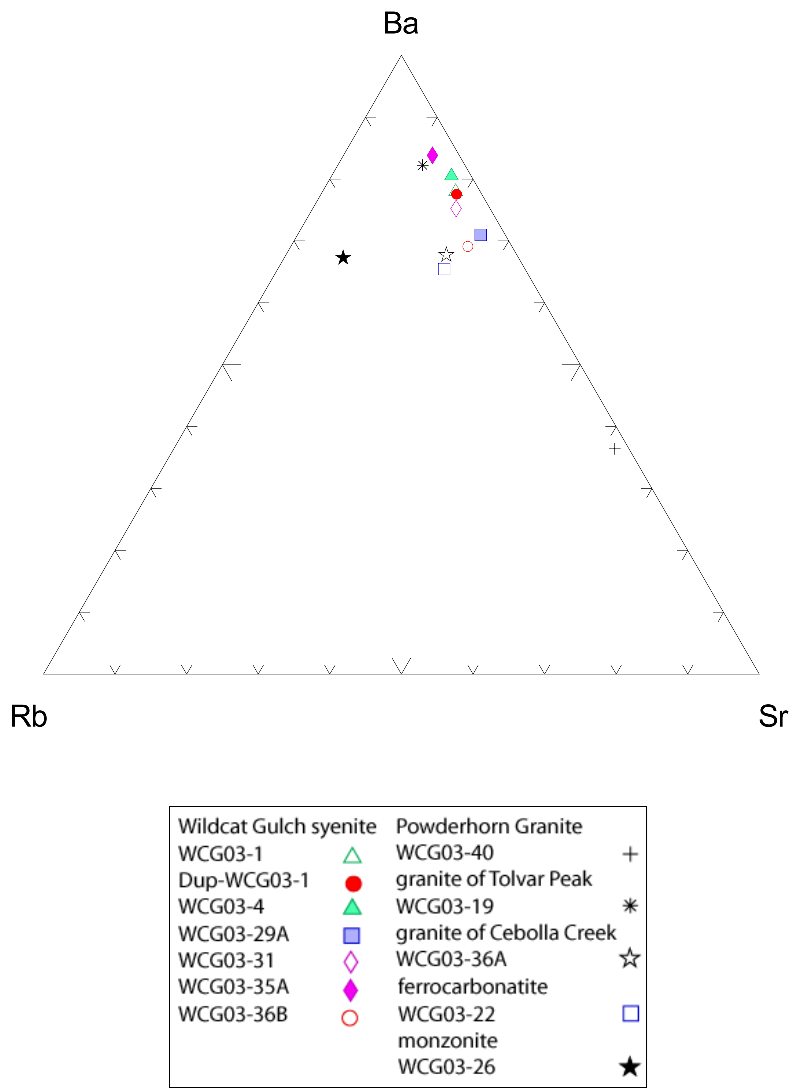


Figure 42. Ba-Rb-Sr ternary diagram for the Wildcat Gulch study area samples.

more closely related to each other than the granite of Cebolla Creek. The Powderhorn Granite and granite of Tolvar Peak have flat HREE at approximately 30 x chondrite while the granite of Cebolla Creek has a more depleted HREE pattern at only 7 x chondrite. The granite of Tolvar Peak has a positive Ce anomaly in comparison to the Powderhorn Granite.

In the N-MORB-normalized trace element plot (Figure 40b), the granite samples are enriched in the mobile large ion lithophile (LIL) elements with respect to the immobile elements. This observation is expected because these elements can readily substitute for K and Na.

The Powderhorn Granite and granite of Tolvar Peak samples have lower Ba concentrations at 232 and 885 ppm, respectively, than the other rocks in the study area. The Powderhorn Granite also has lower Rb (13 ppm), and a very low amount of K_2O (< 1 wt. %). It has less K-feldspar and biotite in the mineral assemblage than the surrounding rocks, which would account for the low concentration of Ba and Rb because these elements commonly substitute for K in K-feldspar and biotite (Siegel 1974).

Ferrocarbonatite and Monzonite

The ferrocarbonatite and monzonite have different rare earth element (REE) patterns (Figure 38a), but similar N-MORB-normalized patterns (Figure 40a). The monzonite and the ferrocarbonatite have crossed REE patterns. Both have LREE enrichment (200 - 800 x chondrite) and similar HREE (Figure 38a). The monzonite has a slight depletion of Eu suggesting either low plagioclase or loss. The ferrocarbonatite shows an increase in Eu possibly a result of substitution of Eu for Ca (Siegel 1974).

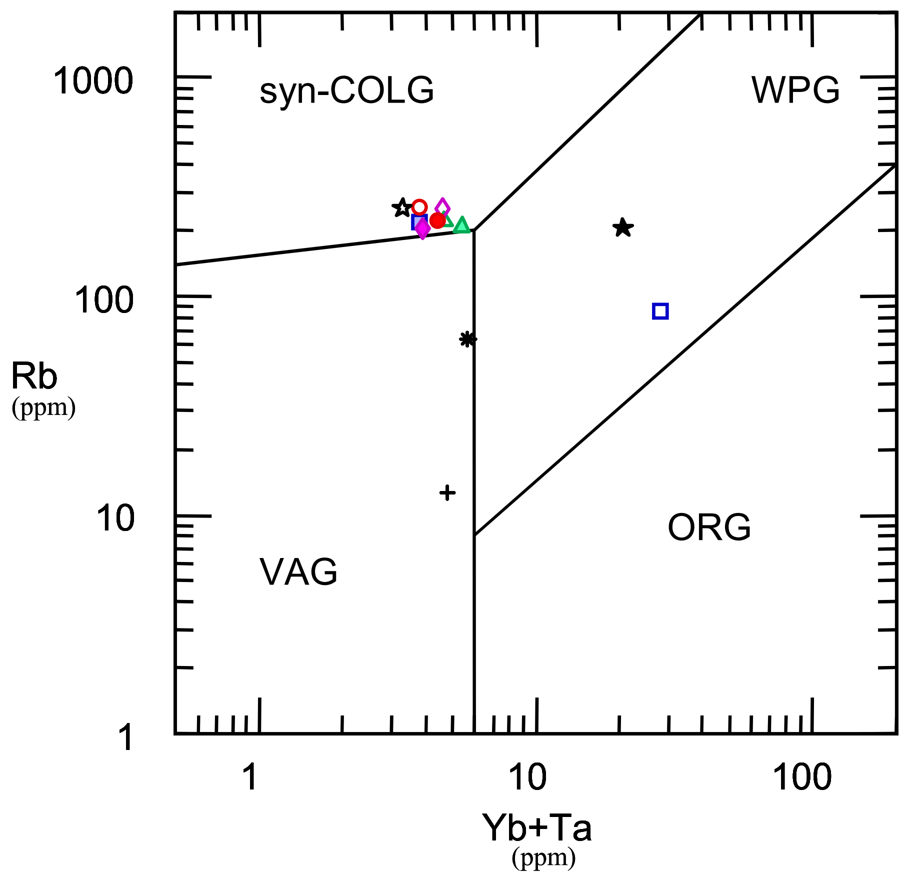
From N-MORB-normalized patterns in Figure 40a, the ferrocarbonatite is similar to the monzonite with lower LIL element concentrations than the syenite or granite samples. Both samples have low Ba and Sr, and the ferrocarbonatite has decreased Zr in comparison to the monzonite.

The ferrocarbonatite has an abundance of Nb and a very low Rb and Sr. These concentrations are comparable with the petrology because the ferrocarbonatite contains no plagioclase. Additionally, the ferrocarbonatite is also low in Ba at 495 ppm, which can be accounted for because the ferrocarbonatite contains less K-feldspar than the syenite samples.

The monzonite has an abundance of Th and Zr, and an abundance of Ga. This observation is expected given that Ga readily substitutes for Al and the monzonite contains the highest concentration of Al_2O_3 of any of the samples (Siegel, 1974). The monzonite also has lower Ba concentrations (566 ppm) in comparison to the other data. The lower Ba concentration is most likely due to the fact that the rock contains less K-feldspar than the other rocks in the area.

Tectonic Discrimination Diagrams

Tectonic discrimination diagrams were utilized in this study to attempt to help place the syenitoid samples into the framework of Proterozoic Colorado geology as well as to compare the syenitoid samples to the other samples of this study. On the Pearce et al. (1984) Rb versus Yb + Ta plot, there are three distinct groupings. The syenitoid rocks and the granite of Cebolla Creek plot within the syn-collisional granitoid field, the ferrocarbonatite and monzonite plot as within-plate granitoids, and the Powderhorn Granite and granite of Tolvar Peak plot as volcanic-arc granitoids (Figure 43).



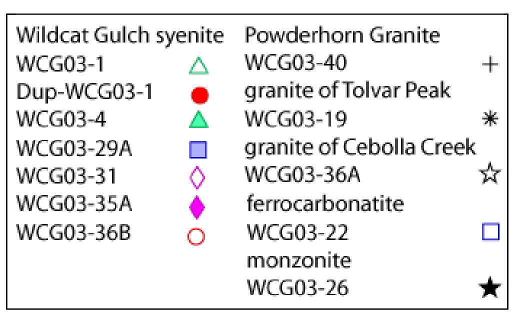


Figure 43. Rb versus Yb + Ta tectonic discrimination diagram after Pearce et al. (1984).

DISCUSSION

Introduction

This chapter presents a discussion and interpretation of both the petrographic and geochemical findings of this study. Additionally, the informal term Wildcat Gulch syenite will be changed in this section to the Wildcat Gulch quartz syenite and quartz monzonite based on the classification of the samples in the PETROLOGY chapter.

For the purpose of a more lucid discussion, only the results that are related to the hypotheses of this study, and those which aid in the placing of the Wildcat Gulch quartz syenite and quartz monzonite within the context of the geology of Colorado will be discussed in this chapter. The results found within the PETROLOGY and GEOCHEMISTRY chapters will be initially discussed separately in the Petrographic Results and Geochemical Results sections of this chapter. The Petrographic Results and Geochemical Results sections will each be discussed in three groups: Wildcat Gulch Quartz Syenite and Quartz Monzonite, Granite, and Ferrocarbonatite and Monzonite. Following these sections, there will be a discussion of the placement of the Wildcat Gulch quartz syenite and quartz monzonite into the Proterozoic Colorado geology framework. Preceding these sections, there is a brief overview of the hypotheses of this study for reference.

Wildcat Gulch Study Hypotheses

The quartz syenite and quartz monzonite of the Wildcat Gulch study area intrude the rocks of the Dubois Greenstone. These intrusions may be related to the formation of the ~1700 Ma Powderhorn Granite and/or granite of Tolvar Peak of the Routt Plutonic Suite and Colorado orogeny of Tweto (1987) and Sims and Stein (2003) respectively.

Alternatively, it is possible that the Wildcat Gulch quartz syenite and quartz monzonite intrusions are related to the syenite samples of Olson et al. (1977) study, which dated three syenite and one biotite-calcite syenite dike at 1390 - 1330 Ma. If the Wildcat Gulch quartz syenite and quartz monzonite intrusions are related to the syenite samples of Olson et al. (1977), this would suggest that the Wildcat Gulch quartz syenite and quartz monzonite intrusions are part of the ~1400 Ma Berthoud Plutonic Suite of Tweto (1987) and the Berthoud orogeny of Sims and Stein (2003).

The third hypothesis suggests that the Wildcat Gulch quartz syenite and quartz monzonite intrusions are related to the ~570 Ma Iron Hill complex. The syenite intrusions of the Iron Hill complex contain nepheline, and if the Wildcat Gulch quartz syenite and quartz monzonite intrusions contain nepheline, it is possible that the intrusions of this study are related to the Iron Hill complex.

If the Wildcat Gulch syenite intrusions are not related to either of these igneous intrusions, then it is possible that they define their own intrusive event.

Petrographic Results

Wildcat Gulch Quartz Syenite and Quartz Monzonite

The quartz syenite and quartz monzonite of the Wildcat Gulch study area intrude the rocks of the Dubois Greenstone. Therefore, it is likely that the Wildcat Gulch quartz syenite and quartz monzonite intrusions are younger than the ~1800 - 1700 Ma Succession. These intrusions consist of two main groups that include a leucocratic quartz monzonite and a melanocratic quartz syenite and quartz monzonite. These descriptions are based on their appearance, mineralogy, and color index. The leucocratic quartz monzonite contains a high percentage of quartz (12 modal %), low percentages of biotite (7 modal %), and no amphibole or pyroxene. The melanocratic quartz syenite and quartz monzonite contains low quartz percents (~ 5 modal %), high concentrations of biotite (up to 14 modal %), and abundant riebeckite (up to 30 modal %). In terms of the classification for igneous rocks by Le Maitre (2002), both groups are actually classified as either quartz monzonite or quartz syenite even though they vary in the amount of mafic minerals.

These classifications are different than the classifications of the syenite rocks that Olson and Hedlund (1973) and Hedlund and Olson (1975) mapped as augite syenite, biotite syenite, quartz syenite and syenite, and melasyenite. While these classifications are more descriptive, the rocks in this study are classified as quartz monzonite or quartz syenite based on their relative percentages of quartz, K-feldspar, and plagioclase.

Of the two varieties of syenitoid rocks within the Wildcat Gulch study area it is likely that the leucocratic quartz monzonite is potentially younger than the melanocratic quartz syenite and quartz monzonite. Many of the melanocratic quartz syenite and quartz monzonite outcrops contain crosscutting syenitoid dikes, which are similar in appearance and mineralogy to the leucocratic quartz monzonite.

Additionally, in their mapping of the Wildcat Gulch study area, Olson and Hedlund (1973) and Hedlund and Olson (1975) place their quartz syenite and syenite (leucocratic quartz monzonite of this study) as relatively younger than their augite syenite, biotite syenite, and melasyenite (melanocratic quartz syenite and quartz monzonite of this study).

The syenitoid outcrop, located along Cebolla Creek and classified by Olson and Hedlund (1973) as a porphyritic augite syenite surrounded by melasyenite, is classified in this study as a quartz syenite. Olson and Hedlund (1973) describe multiple syenite lithologies at this location. In this study, only two lithologies were present, a quartz syenite and a granite. The granite found intercalated with this quartz syenite intrusion is not mentioned by Olson and Hedlund (1973). Based on outcrop appearance, it is uncertain which unit intruded first because both lithologies are intermixed. It is possible that the quartz syenite could have undergone fractional crystallization to form the granite. Alternatively, it is possible that the granite may have assimilated mafic material to form the quartz syenite. It is also possible that this outcrop represents two separate immiscible magmas that were intruding at the same time.

Petrographically, the syenitoid rocks of this study contain a greater amount of the biotite and riebeckite in comparison to the Powderhorn Granite and granite of Tolvar Peak, which have < 10 % biotite and no riebeckite. This observation suggests that if the syenitoid rocks evolved from these granite intrusions, they must have assimilated mafic material because the syenitoid rocks of this study are dominantly intermediate to mafic in composition. While evidence of assimilation may exist in the form of a mafic enclave in the leucocratic quartz monzonite, it is unlikely that the magma would be sufficiently hot enough to melt the mafic material necessary to achieve the abundances of biotite and riebeckite that are observed in the Wildcat Gulch quartz syenite and quartz monzonite. Therefore, while possible, it is less likely that the syenitoid samples evolved from the Powderhorn Granite or granite of Tolvar Peak. This hypothesis suggests that the syenitoid intrusions of the Wildcat Gulch study area may not be related to the rocks of the Colorado Orogeny, which formed the ~1700 Ma Powderhorn Granite and granite of Tolvar Peak intrusions.

While these petrographic comparisons potentially rule out a Powderhorn Granite or granite of Tolvar Peak source for the Wildcat Gulch quartz syenite and quartz monzonite, they may also suggest that the Wildcat Gulch quartz syenite and quartz monzonite have a mafic source because the syenitoid rocks are so abundant in mafic minerals.

Of the analyzed syenitoid samples, there were no feldspathoids observed in either the quartz monzonite or the quartz syenite. The samples of this study all contain varying percentages of quartz and no feldspathoids. This lack of nepheline would suggests that the Wildcat Gulch study area intrusives are not related to the syenite of the ~570 Ma Iron Hill complex to the south of the field area that contains nepheline syenite.

In comparison to the syenite samples described by Hunter (1925), Olson and Hedlund (1973), Hedlund and Olson (1975, 1981), and Olson et al. (1977), the syenitoid rocks of this study are petrographically similar. They differ in that the syenite of Hunter (1925), Olson and Hedlund (1973), Hedlund and Olson (1975, 1981), and Olson et al. (1977) contain abundant augite while the samples of this study contain riebeckite. Also in their descriptions of the syenite, Olson and Hedlund (1973) and Hedlund and Olson (1975) do not indicate whether or not plagioclase is present. However, through petrographic analyses, it was determined that the quartz monzonite and quartz syenite intrusions of this study contain abundant plagioclase.

Because several samples from this study were obtained from the sites of Hunter (1925) and Olson et al. (1977), it is likely that their syenite rocks are equivalent to the quartz monzonite and quartz syenite of this study, and the mineralogical discrepancies that exist may only be either the result of misinterpretation of mineralogy, mineralogic variability within each outcrop, or simply that the classifications of Olson and Hedlund (1973), Hedlund and Olson (1975, 1981), and Olson et al. (1977) are "field classifications" and not classifications based on thin section analyses.

It should be noted that this is not a negative assessment of the previous research of Olson and Hedlund (1973), Hedlund and Olson (1975, 1981), and Olson et al. (1977). These researchers have drafted fine geologic maps of the area, and laid the framework for this study through their K-Ar biotite mineral separate dating and major element geochemical data. The preceding statement only implies that in outcrop and hand sample observations it is virtually impossible to tell the difference between K-feldspar and plagioclase, as well as amphibole or pyroxene, because both minerals appear the same mesoscopically in the Wildcat Gulch study area samples.

In unstained thin sections, the lack of feldspar twinning made the determination of K-feldspar versus plagioclase difficult because both minerals appear the same in the Wildcat Gulch sample thin sections. However, through staining of the thin sections for feldspars, it became easier to determine K-feldspar from plagioclase. Because Olson and Hedlund (1973), Hedlund and Olson (1975), and Olson et al. (1977) do not state that they used stained thin sections for feldspar evaluation, it is likely that they may have misinterpreted the mineralogy of the samples, which would lead to differences in classification. These differences in classifications of the syenitoid rocks of the Wildcat Gulch study area are not significant enough to suggest that the quartz monzonite and quartz syenite of this study are separate intrusions from the mapped syenitoid rocks of Olson and Hedlund (1973) and Hedlund and Olson (1975).

It is therefore suggested that the quartz monzonite and quartz syenite of this study are correlative with the rocks of the Olson and Hedlund (1973), Hedlund and Olson (1975, 1981), and Olson et al. (1977) studies. This hypothesis implies that the quartz monzonite and quartz syenite of this study have similar ages to the rocks dated in the Olson et al. (1977) study. If true, this would place the ages of the quartz monzonite and quartz syenite at 1390 - 1330 Ma. This suggests that the quartz monzonite and quartz syenite are placed within the Berthoud Plutonic Suite of the Precambrian X, and are related to the ~1400 Ma Berthoud orogeny of Sims and Stein (2003).

Granite

The Powderhorn Granite and granite of Tolvar Peak samples in this study are petrogaphically classified as granite. The granite of Tolvar Peak, within the field area, does not contain evidence of foliation in any sample collected in this study. This does not preclude the possibility that the granite of Tolvar Peak is foliated elsewhere.

As mentioned in the PETROLOGY chapter, most mapped outcrops of the Powderhorn Granite consist of finely-crystalline felsic schist, and that only one Powderhorn Granite outcrop was a phaneritic granite. It is possible that both the Powderhorn Granite and granite of Tolvar Peak intrusions were subjected to varying degrees of strain partitioning that produced foliation in some areas, but not in others. If true, this may account for the reason why the granite of Tolvar Peak is not foliated within the field area, and why most outcrops of Powderhorn Granite are schistose.

As mentioned in the previous section, an additional granite outcrop occurs within a mapped syenite outcrop of Olson and Hedlund (1973). This granite may be related to either the Powderhorn Granite or granite of Tolvar Peak intrusions, or it may be an unrelated intrusion. However, no definitive conclusions could be drawn from the petrology because all granite samples in the area contain a basic granite assemblage of quartz, K-feldspar, and plagioclase. The, informally named, granite of Cebolla Creek does differ from the other granite intrusions in the area in that it contains up to 7 % riebeckite, which is similar to that found within the syenitoid rocks of the study.

Ferrocarbonatite and Monzonite

The carbonatite in this study is classified based on the classification scheme of Le Maitre (2002) as a ferrocarbonatite. In the study of U deposits in the Gunnison area, Goodknight

(1981) describes an Fe-rich vein that crosscuts a leucosyenite intrusion at the location of the ferrocarbonatite. Goodknight (1981) further states that this Fe-rich vein, which contains uranium, is related to the Iron Hill complex. This suggests that this iron-rich outcrop (ferrocarbonatite) is related to the Iron Hill complex carbonatite. The close geographic proximity of the Iron Hill complex, as well as the presence of hematite, also suggest that the ferrocarbonatite in the Wildcat Gulch study area is related to the ~570 Ma Iron Hill complex because the rocks of the Iron Hill complex contain high concentrations of Fe and hematite, and is the only source of carbonatite in the area (Cappa, 1998).

Additionally, because it is likely that the ferrocarbonatite is related to the Iron Hill complex, this lends further evidence that the Wildcat Gulch syenite rocks are not related to the rocks of the Iron Hill complex because the iron-rich vein is observed to crosscut the leucosyenite outcrop (Goodknight, 1981).

Within the Wildcat Gulch study area, two outcrops exist of what are petrographically classified in this study as monzonite based on the classification scheme of Le Maitre (2002). One outcrop occurs as an intrusion into the granite of Tolvar Peak, while the other occurs along Highway 149, south of Nine Mile Hill within the amphibolite (mafic lithodeme) of the Dubois Greenstone. Hedlund and Olson (1975) classify this rock as a trachyte. A trachyte is a rock that contains a K-feldspar to plagioclase ratio of 4 to1 or greater, or a rock that has a trachyitic texture (Compton, 1985). Through petrographic analysis, these outcrops contained a plagioclase to K-feldspar ratio of almost 2 to1. This would suggest that the classification of this rock as a trachyte is incorrect. However, these samples did have a trachyitic texture, which is often used to classify rocks of this nature as trachyte. Therefore, the classification of this rock as a trachyte is valid based upon the texture. In this study, however, samples were classified based on the

QAP classification scheme of Le Maitre (2002). Based on this classification scheme, and the observation that at least one of these outcrops is intrusive in nature, these rocks are classified as monzonite.

The intrusive nature of the monzonite outcrop within the granite of Tolvar Peak suggests that this unit has a younger age than the granite of Tolvar Peak. This implies that the monzonite is younger than ~1700 Ma. Additionally, Nelson and Riesmeyer (1983) state that carbonatite and trachyte dikes within the area are related to the Iron Hill complex. If true, this suggests that the monzonite outcrops in the Wildcat Gulch study area are related to the ~570 Ma Iron Hill complex.

These monzonite outcrops are vastly different both petrographically and geochemically from the quartz monzonite and quartz syenite intrusions. The monzonite is a felsic mineral dominated rock while the quartz monzonite and quartz syenite contain abundant biotite and riebeckite.

Based upon crosscutting relationships and previous research, a relative stratigraphic sequence to the rocks of the Wildcat Gulch study area can be derived. As the Dubois Greenstone lithodemes are intruded by the granite of Tolvar Peak, the Wildcat Gulch quartz syenite and quartz monzonite, the monzonite outcrop along Highway 149, and Ordovician diabase dikes, it is most likely that the Dubois Greenstone is the oldest formation in the study area. Following the formation of the Dubois Greenstone would be the granite of Tolvar Peak and the Powderhorn Granite based on previous research and the crosscutting relationships. As the syenitoid rocks of the study area intrude the Dubois Greenstone, and are intruded by the carbonatite of Goodknight (1981), it is likely that the Wildcat Gulch quartz syenite and quartz monzonite intruded after the granite intrusions of the Routt Plutonic Suite. This hypothesis is supported by the K-Ar biotite mineral separate dates of 1390 - 1330 Ma of Olson et al. (1977). The next event in the study area would be the intrusion of the ferrocarbonatite and monzonite that are hypothesized to be related to the Iron Hill complex. Following these intrusions would be the Ordovician diabase dikes and the deposition of the Tertiary Sapinero Mesa Tuff.

This relative stratigraphic sequence also aids in adding further evidence that the Wildcat Gulch quartz syenite and quartz monzonite are not related to the intrusion of the Powderhorn Granite, granite of Tolvar Peak, or the Iron Hill complex.

Geochemical Results

In the GEOCHEMISTRY chapter the Wildcat Gulch study area rocks were classified using CIPW normative calculations and AFM and TAS diagrams. In comparison to the mineralogical classifications, the CIPW normative-based classifications contain lower percentages of quartz and plagioclase with respect to the syenitoid and the monzonite samples. Even though the quartz and plagioclase percentages are less in the CIPW normative calculations, the classifications are not that dissimilar to the mineralogical classifications. Essentially, there is up to 5 % difference in the amounts of quartz calculated using the CIPW-normative calculation software in IgPet 2001, in comparison to that of the mineralogical modal analyses. This error may be due to the experimental error involved in performing 100 point modal analyses.

In contrast, the Powderhorn Granite and granite of Tolvar Peak samples contain higher quartz and plagioclase percentages in the CIPW normative calculation in comparison to the modal analyses (Figure 18). These differences however, are greater with respect to the percentage of quartz, which is up to 20 % different from the modal analyses. These differences in quartz percentages may be a result of the way in which the computer software calculated the percentage of quartz, or due to the error involved in performing a 100 point modal analysis.

In the AFM diagrams (Figure 19), the syenitoid and granitoid rocks, as well as the rocks of the Dubois Greenstone, plot within the calc-alkaline field. The rocks of the Dubois Greenstone, however, plot in two distinct fields. This suggests that the rocks of the Dubois Greenstone are bimodal in nature. This bimodality has been recognized by previous researchers and is seen in the PETROLOGY chapter, which describes the Dubois Greenstone as being dominantly metamorphosed basaltic and rhyolitic rocks.

From the TAS diagrams, it can be hypothesized that the Wildcat Gulch quartz syenite and quartz monzonite intrusions evolved from a parent magma similar to that of the mafic Dubois Greenstone lithodeme because the syenitoid rocks show a trend from the more mafic melanocratic quartz syenite and quartz monzonite, which plots near the mafic lithodeme of the Dubois Greenstone, to the leucocratic quartz monzonite. This trend may also suggest that the leucocratic quartz monzonite evolved from the melanocratic quartz syenite and quartz monzonite, and that all syenitoid varieties in the area are related. If so, then it is likely that the leucocratic quartz monzonite evolved from the melanocratic quartz syenite and quartz monzonite, which may have evolved from a basaltic parent magma similar to that of the mafic Dubois Greenstone lithodeme through fractional crystallization processes. This relationship may suggest that these rocks have a similar source region to the rocks of the Dubois Greenstone, but formed at a later date. Alternativly, these trends may only reflect the overall major mineralogy of the rocks.

Wildcat Gulch Quartz Syenite and Quartz Monzonite

In terms of their major element oxide weight percentages, the data suggest that the syenitoid rocks contain an abundance of both K-feldspar and plagioclase because the rocks contain high percentages of SiO_2, Al_2O_3, CaO, and K_2O (Table 9). In addition, the abundance of MgO and Fe_2O_3 suggest that there is a significant amount of ferromagnesian minerals present. Both observations are reflected in the petrology, which contains abundant K-feldspar (microcline), plagioclase, biotite, and riebeckite.

It is hypothesized that the leucocratic quartz monzonite may have evolved from the melanocratic quartz syenite and quartz monzonite because the leucocratic quartz monzonite is more enriched in K_2O, Na_2O, Al_2O_3 , and SiO_2 and depleted in CaO, MgO, and Fe_2O_3 (Table 9) with respect to the melanocratic quartz syenite and quartz monzonite. This relationship may suggest that the syenite evolved through fractional crystallization and possibly assimilation from a single source at depth. Alternatively, it is possible that this relationship is merely the result of the mineralogic composition of the two syenitoid varieties.

The Wildcat Gulch quartz syenite and quartz monzonite are geochemically similar to the syenite samples of Hunter (1925), Olson et al. (1977), and Hedlund and Olson (1981). They differ only in terms of MgO and Na_2O. The Wildcat Gulch quartz syenite and quartz monzonite is depleted in terms of MgO with respect to the samples of Hedlund and Olson (1981). This is most likely a function of the mafic mineral phases. The Wildcat Gulch samples are enriched in biotite and riebeckite, while the samples of Hedlund and Olson (1981) are reported to contain more augite and hornblende.

Because the syenite samples of Hedlund and Olson (1981) and the samples of this study are geochemically similar, it is possible that they are related. If so, then it is likely that the

Wildcat Gulch quartz syenite and quartz monzonite formed during the same time as the syenite samples of Olson et al. (1977) as previously discussed. This would place the age of the Wildcat Gulch quartz syenite and quartz monzonite intrusions at 1390 - 1330 Ma within the ~1400 Ma Berthoud orogeny of Sims and Stein (2003).

Upon comparison with the geochemical data of Condie and Nuter (1981) on the Dubois Greenstone rocks, the syenitoid geochemistry is similar to the data of Condie and Nuter (1981), implying that the syenitoid rocks evolved through fractional crystallization of a basaltic parent magma similar to that of the mafic lithodeme of the Dubois Greenstone. This observation is apparent in the previous discussion of the TAS diagrams (Figure 20).

The Wildcat Gulch quartz syenite and quartz monzonite samples have, in several instances, a correlation with the Dubois Greenstone geochemistry from Condie and Nuter (1981). The Na_2O, CaO, MgO, Al_2O_3, SiO_2 and TiO_2 values of the syenitoids appear to have been influenced by the mafic and felsic lithodemes of the Dubois Greenstone because their oxide values are similar. However, the Fe_2O_3 and K_2O oxides show no connection with the Dubois Greenstone. This observation could be a function of the differences in mafic minerals of the Dubois Greenstone versus the syenitoid samples in terms of the Fe_2O_3, and the K_2O is different most likely as a result of the presence of microcline in the syenitoids. Alternatively, the Fe_2O_3 concentrations may be a function of the difficulty of mobilizing Fe, or how the Fe values were geochemically reported. However, overall there is a strong correlation between the Wildcat Gulch syenite samples and the data for the mafic lithodeme of the Dubois Greenstone from Condie and Nuter (1981).

The trace element geochemical plots of Ba versus K_2O (Figure 35), Rb versus K_2O (Figure 34), Rb versus Sr (Figure 29), and Sr versus Eu (Figure 33) suggest that there is a possibility that the syenitoid intrusions may have formed from the same magmatic source as the Powderhorn Granite and granite of Tolvar Peak, and have evolved through fractionation processes. If these elements within the granititc magma are fractionated, it is hypothetically possible to attain the concentrations of these elements that are seen in the syenitoid samples from the granite of Tolvar Peak and Powderhorn Granite samples. This could suggest that the syenitoid intrusions may have evolved from these granite intrusions. However, these trends may simply be an artifact from the fact that syenitoid rocks are naturally enriched in these elements due to their mineralogy with little regard to their source material (Siegel, 1974). Additionally, even though the geochemistry may suggest that the syenitoid intrusions may be related to the granite intrusions, it is unlikely that the syenitoid rocks evolved from the granite intrusions based on the difficulty of assimilating the necessary mafic material to form the mineralogic composition of the syenitoids.

The plot of V versus Fe_2O_3 (Figure 36) shows an enrichment trend from the granite and monzonite samples to the leucocratic quartz monzonite, and from the leucocratic quartz monzonite to the melanocratic quartz syenite and quartz monzonite and the ferrocarbonatite. This trend may represent a fractionation trend from a single source material, or it may merely be a function of the mineralogy of the various rocks. Given the previous petrographic discussion against the possibility of a Powderhorn Granite or granite of Tolvar Peak source for the syenitoid rocks, it is likely that this plot is simply a result of the mineralogy of the various samples and their relationship to each other.

The Wildcat Gulch quartz syenite and quartz monzonite samples contain high concentrations of Ba. These concentrations, while higher than the average Ba concentration of 1600 ppm in syenite of Siegel (1974), are not unreasonable given that Ba is very mobile and readily substitutes for K in K-feldspar, hornblende, and especially in biotite. Given that the Wildcat Gulch quartz syenite and quartz monzonite samples contain high percentages of these minerals, the elevated Ba concentrations would be expected. Also as syenitoid intrusions typically form from differentiation processes, it would be expected that their Ba concentrations would be elevated as a result of Ba mobility that concentrates it in the magma (Siegel, 1974).

The Wildcat Gulch quartz syenite and quartz monzonite also contain elevated V concentrations. According to Siegel (1974), the average V concentration in syenite is 30 ppm. The Wildcat Gulch quartz syenite and quartz monzonite contain 96 to 201 ppm V (Table 9). This could lend evidence to the hypothesis of assimilation of the rocks of the Dubois Greenstone because basalts are typically high in V having concentrations up to approximately 300 ppm in calc-alkaline basalt (Mason, 1966). An alternative hypothesis for these elevated V concentrations is that the syenitoid intrusions could have evolved from a basaltic parent magma.

According to Krauskopf (1967), it is possible to generate alkalic magma and syenite from the differentiation of basaltic magma low in silica. Additionally, given the previous discussions, it is more likely that the syenitoid rocks evolved from a mafic basaltic magma similar to that of the Dubois Greenstone.

The Wildcat Gulch quartz syenite and quartz monzonite trace element data indicate that even though they vary slightly mineralogically, the Wildcat Gulch quartz syenite and quartz monzonite are similar geochemically with some variations due most likely to variability of trace element substitution. The data suggests that both the leucocratic quartz monzonite and the melanocratic quartz syenite and quartz monzonite may all have formed from the same magma source through fractional crystallization and assimilation or from immiscible fluids. If the syenitoid formed from immiscible fluid processes from the Powderhorn Granite or the granite of

Tolvar Peak, the trace element geochemistry should be vastly different. This is not the case; the syenitoid and the granite intrusions have similar trace element patterns. These patterns suggest that the syenitoid did not form from an immiscible fluid from either granite body.

The Wildcat Gulch quartz syenite and quartz monzonite in the plots of Nb versus Ta (Figure 31) and Hf versus Zr (Figure 32) plot close to the average crustal ratios of Nb/Ta $\approx$12 and Zr/Hf $\approx$33 (Taylor and McLennan, 1985). This could suggest that the rocks of the study area formed as intrusions into crustal material or in a crustal setting. These plots may support the hypothesis that the Wildcat Gulch quartz syenite and quartz monzonite are most likely related to the rocks of the ~1400 Ma Berthoud orogeny, which formed in a continental setting.

Granite

The Powderhorn Granite and granite of Tolvar Peak intrusions are similar in both their major and trace element concentrations. It is possible that this relationship suggests that the two granite intrusions are related. This hypothesis is supported because research indicates that both granite bodies formed during the same time frame and tectonic setting (Tweto, 1980b; Hedlund and Olson, 1981).

The granite samples have low Nb, which could suggest an arc environment. This agrees with the work of Tweto (1980b) and Sims and Stein (2003) who state that during the Precambrian (Proterozoic) in Colorado, there were various periods of arc collision and accretion.

Ferrocarbonatite and Monzonite

The monzonite is very depleted in CaO and MgO (Table 10) compared to the other rocks in the study. This agrees with the formation of Heinrich and Moore (1970) “red rock” or metasomatic “feldspar rock” formation. There is elevated aluminum, sodium, and potassium, and depleted calcium and magnesium. However, the sample contains an abundance of silica and a minor amount of iron, which does not fit with the formation of metasomatic feldspar rocks. It is possible that the rocks were undergoing metasomatism, and for some reason the process terminated before the excess silica could be removed. However, aside from the rocks unusual color, no metasomatic evidence exists in thin section. Alternately, it is possible that these intrusions are simply late stage magmas, and the geochemistry could be a function of the anti-rapikivi texture and the evolution of the magmatic source.

All of the rocks of the study have similar trace element patterns with the exception of the ferrocarbonatite. All of the REE patterns are similar with elevated LREE between 100 - 800 x chondrite and relatively flat HREE patterns near 20 x chondrite with the exception of the ferrocarbonatite (Figure 38). This could suggest that all of these rocks are related in terms of their source material or tectonic mode of emplacement.

In the N-MORB-normalized plot (Figure 40) a similar relationship is seen between the granite and the syenitoid rocks, which have very similar patterns. These observations may support the hypothesis that the syenitoid samples may have evolved from either the Powderhorn Granite or granite of Tolvar Peak because their trace element results are similar.

The Wildcat Gulch quartz monzonite and quartz syenite have similar REE patterns in comparison to the USGS standard nepheline syenite STM-1 data of Smith (1995). The similar REE patterns may suggest that the Wildcat Gulch quartz syenite and quartz monzonite are not that dissimilar to a nepheline syenite in terms of REE. However, in the N-MORB-normalized plot, the Wildcat Gulch quartz syenite and quartz monzonite are more distinctly different from STM-1. These data suggest the possibility that the Wildcat Gulch quartz syenite and quartz monzonite have some similarities and differences to nepheline syenite trace element geochemical data. This could imply that the Wildcat Gulch quartz syenite and quartz monzonite may not be related to the nepheline syenite of the Iron Hill complex. However, this is only weak evidence at best given that the actual data from the nepheline syenite of the Iron Hill complex could not be obtained in this study.

The three data groupings observed in the tectonic discrimination diagram may represent three distinct magmatic episodes (Figure 43). The first of these occurring as the ~1700 Ma granite intrusions of the Routt Plutonic Suite (Powderhorn Granite and granite of Tolvar Peak). The second being the ~1400 Ma intrusions of the Berthoud Plutonic Suite (syenitoid and granite of Cebolla Creek). The final episode is the intrusion of the ferrocarbonatite and monzonite associated with the ~570 Ma Iron Hill complex. The volcanic-arc granitoid grouping correlates well with the hypothesis that the Routt Plutonic Suite plutons intruded during an episode of arc collision and accretion to the Archean Wyoming craton. In addition, the syenitoid samples plot in the syn-collisional granitoid field, which may add evidence to the hypothesis that the rocks formed as part of the Berthoud Plutonic Suite and Berthoud orogeny. Lastly, the grouping of the ferrocarbonatite and monzonite into the within-plate granitoid field may add further evidence to these rocks being related to the Iron Hill complex, which formed in an intraplate setting.

Placement of the Syenitoid Plutons Within the Geology of Colorado

Syenitoid magma can form in three ways (Krauskopf, 1967). Alkalic magma may form from a granitic magma rich in volatiles because the volatiles separate out the alkali material as an immiscible fluid (Krauskopf, 1967). Alternatively, Krauskopf (1967) states that alkalic magma may be formed from the assimilation of limestone. In addition, Krauskopf (1967) states that it is also possible to generate alkalic magma and syenite from the differentiation of basaltic material low in silica.

In attempting to determine the source material for the Wildcat Gulch quartz syenite and quartz monzonite, it was found that through geochemical analyses the intrusions may have evolved through fractional crystallization from a single magma source based on the major and trace element analyses. The major element oxides all show a trend from more mafic melanocratic syenitoid to more felsic leucocratic syenitoid, which may suggest fractional crystallization processes from a single magma source at depth.

Possible sources for the Wildcat Gulch quartz syenite and quartz monzonite, as previously discussed, are either the Powderhorn Granite, the granite of Tolvar Peak, or the Iron Hill complex. The Wildcat Gulch quartz syenite and quartz monzonite may also define their own separate intrusive event with a source not related to either of previously mentioned igneous bodies.

As previously discussed, it is unlikely that the Wildcat Gulch quartz syenite and quartz monzonite formed from either the rocks of the Powderhorn Granite or granite of Tolvar Peak intrusions. This suggests that it is unlikely that the Wildcat Gulch quartz syenite and quartz monzonite formed from a granitic magma because no other significant granitic sources exist in the area.

Additionally, the Iron Hill complex has been ruled out as a possible source for the Wildcat Gulch quartz syenite and quartz monzonite based on the lack of nepheline in the Wildcat Gulch quartz syenite and quartz monzonite, and the previous discussion of the iron-rich carbonatite intrusion of the Goodknight (1981) study.

The elimination of both the Powderhorn Granite and granite of Tolvar Peak intrusions, as well as the elimination of the Iron Hill complex, suggests that the Wildcat Gulch quartz syenite and quartz monzonite defines its own intrusive event. Based on the dominantly mafic composition of the rocks, the geochemical relationships discussed in the previous section, and the work of Olson et al. (1977) and Krauskopf (1967), it is likely that the syenite formed from a mafic basaltic source during the ~1400 Ma Berthoud Orogeny.

Based on the work of Bailey (1974), Cappa (1998), and Beane and Wobus (1999), which states that syenite can form in rift environments, fault zones, subduction zones, and in areas of continental uplift, the possible tectonic environment of formation for the Wildcat Gulch quartz syenite and quartz monzonite can be constrained.

Within the Wildcat Gulch study area there are several faults (Olson and Hedlund, 1973; and Hedlund and Olson (1975). These faults are located near many of the syenitoid outcrops. It is therefore possible that the Wildcat Gulch quartz syenite and quartz monzonite intruded along these fault lines in a continental extensional setting similar to the Sugarloaf Syenite of the Pikes Peak Batholith (Beane and Wobus, 1999).

Because syenite can form in a subduction zone environment, it is possible that syenitoid rocks could have formed in this environment. However, as Cappa (1998) states, alkaline magma is only a minor part of subduction magmatism. If these intrusions formed in a subduction zone environment, then there should be some additional granitoid magma. The only main granitic magmas are the ~1700 Ma Powderhorn Granite and granite of Tolvar Peak. As these granite bodies are 300 Ma older than the Wildcat Gulch quartz syenite and quartz monzonite, and previous discussion of the problem of assimilation, it is unlikely that the Wildcat Gulch quartz syenite and quartz monzonite are related to the granite or a subduction zone environment unless they formed through shallow subduction processes, and the subduction zone is farther to the south.

Based on these tectonic scenarios, and the strong evidence that the Wildcat Gulch quartz syenite and quartz monzonite are related to the 1390 - 1330 Ma syenite of Olson et al. (1977), which is part of the Berthoud orogeny of Sims and Stein (2003), it is most likely that the Wildcat Gulch quartz syenite and quartz monzonite formed in an extensional, continental environment and possibly intruded along faults.

CONCLUSIONS

Based on the petrographic and geochemical analyses of the Wildcat Gulch syenite, and the surrounding country rocks, the following conclusions can be drawn.

1. Based upon resampling of syenitoid outcrops of Hunter (1925) and Olson et al. (1977), and the samples obtained in this study, the Wildcat Gulch syenite intrusions are petrographically classified as quartz syenite and quartz monzonite.
2. Major element analyses of this study are similar to the syenite data of Hunter (1925) and Olson et al. (1977)
3. The trace element results of this study provide evidence that the syenitoid intrusions within the Wildcat Gulch study area are similar, suggesting that they formed as the same event.
4. The ~1700 Ma Powderhorn Granite or Tolvar Peak granite intrusions are unlikely sources for the Wildcat Gulch quartz syenite and quartz monzonite based upon the mineralogic and geochemical data.
5. It is unlikely that the Wildcat Gulch quartz syenite and quartz monzonite are related to the syenite of the Iron Hill complex based upon the mineralogic data and literature comparisons.
6. The field relationships and geochemical data, coupled with the K-Ar dates on biotite separates of 1390 - 1330 Ma of Olson et al. (1977) suggest that the Wildcat Gulch syenite intruded as part of the ~1400 Ma Berthoud orogeny of Sims and Stein (2003).

7. The Powderhorn Granite and granite of Tolvar Peak are nonfoliated within the field area. These intrusions plot as granite both petrographically and geochemically.
8. The ferrocarbonatite is likely from the Iron Hill complex, which would place its intrusion age at approximately ~570 Ma.
9. The monzonite formed as an intrusion into the granite of Tolvar Peak and the mafic lithodeme of the Dubois Greenstone, and may be related to the Iron Hill complex.
10. The Wildcat Gulch quartz syenite and quartz monzonite may have formed through fractional crystallization of a basaltic parent magma.
11. The Wildcat Gulch quartz syenite and quartz monzonite may have formed in an extensional, continental environment, and possibly intruded along faults.

REFERENCES CITED

Armbrustmacher, Theodore J., 1981, The Complex of Alkaline Rocks at Iron Hill, Powderhorn District, Gunnison County, Colorado, *in* Beus, Stanley S., ed., New Mexico Geological Society Guidebook, 32nd Field Conference, Western slope Colorado, p. 293-296.

Armbrustmacher, Theodore, J., and Shannon, Jr., Spencer S., 1987, The carbonatite complex at Iron Hill, Powderhorn District, Gunnison County, Colorado, *in* Epis, Rudy C. and Callender, Jonathan F., eds., Geological Society of America Centennial Field Guide—Rocky Mountain Section, p. 325-327.

Bailey, John C. 1974, Continental Rifting and Alkaline Magmatism, *in* Sorensen, H., ed., The Alkaline Rocks, New York, New York, J. Wiley and Sons, p.148-159.

Bailey, Edgar, H. and Stevens, Rollin E., 1960, Selective Staining of K-feldspar and Plagioclase on Rock Slabs and Thin Sections, American Mineralogist, v. 45, p. 1020-1025.

Beane, Rachel and Wobus, Reinhard A., 1999, Petrogenesis of the Sugarloaf Syenites, Pikes Peak batholith, Colorado, Rocky Mountain Geology, v. 34, no. 2, p. 313-324.

Bickford, M. E. and Boardman, S. J. 1984, A Proterozoic Volcano-Plutonic Terrane, Gunnison and Salida Areas, Colorado, Journal of Geology, v. 92, p. 657-666.

Boardman, Shelby J. and Condie, Kent C. 1986, Early Proterozoic Bimodal Volcanic Rocks in Central Colorado, U.S.A., Part II: Geochemistry, Petrogenesis and Tectonic Setting, Precambrian Research, v. 34, p. 37-68.

Cappa, James A., 1998, Alkalic Igneous Rocks of Colorado and Their Associated Ore Deposits, Resource Series 35, Colorado Geological Survey, Denver Colorado, p. 138.

Compton, Robert R., 1985, Geology in the Field, New York, New York, John Wiley and Sons, p. 398.

Condie, Kent C., and Nuter, Janet A., 1981, Geochemistry of the Dubois Greenstone Succession: An Early Proterozoic Bimodal Volcanic Association in West-Central Colorado, Precambrian Research, v.15, p. 131-155.

Goodknight, Craig S., 1981, Uranium in the Gunnison Country, Colorado, *in* Epis, Rudy C. and Callender, Jonathan F., eds., New Mexico Geological Society Guidebook, 32nd Field Conference, Western slope Colorado, p. 183-189.

Hedlund, D.C. and Olson, J.C., 1975, Geologic map of the Powderhorn Quadrangle, Gunnison and Saguache Counties, Colorado, United States Geological Survey Map GQ 1178.

Hedlund, D.C., and Olson, J. C. 1981, Precambrian Geology along Parts of the Gunnison Uplift of Southwestern Colorado, *in* Epis, Rudy C. and Callender, Jonathan F., eds., New Mexico Geological Society Guidebook, 32nd Field Conference, Western slope Colorado, p. 267-272.

Heinrich, E. W. M. and Moore, Jr., D. G., 1970, Metasomatic potash feldspar rocks associated with igneous alkaline complexes, Canadian Mineralogist, v. 10, p. 571-584.

Hill, Barbara M., and Bickford, M. E., 2001, Paleoproterozoic rocks of central Colorado: Accreted arcs or extended older crust?, Geology, v. 29, no. 11, p. 1015-1018.

Hunter, Fred J., 1925, Pre-Cambrian Rocks of Gunnison River Colorado, US Geological Survey Bulletin 777, Reston, Virginia, USGS, p. 94.

Krauskopf, Konrad Bates, 1967, Introduction to Geochemistry, New York, New York, McGraw-Hill Publishing, p. 721

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A, and Zanettin, B.A., 1986, Chemical classification of volcanic rocks based on the total alkai-silica diagram, Journal of Petrology, v. 22, no 3, p. 745-750.

Le Maitre, R. W., 2002, Igneous Rocks: A Classification and Glossary of Terms, Cambridge, United Kingdom, Cambridge University Press, p. 236.

Mason, Brian, 1966, Principles of Geochemistry, New York, New York, John Wiley and Sons, p. 329.

McLemore, Virginia T. and McKee, Christopher 1989, Geology and Geochemistry of Syenites and Adjacent Proterozoic Granitic and Metamorphic Rocks in the Zuni Mountains, Cibola Country, New Mexico, *in* Epis, Rudy C. and Callender, Jonathan F., eds., New Mexico Geological Society Guidebook, 40th Field Conference, p. 149-155.

Nakamura, N., 1974, Determination of REE, Ba, RE, Mg, Na, and K in carbonaceous and ordinary chondrite, Geochemica et Cosmochemica Acta, v. 38, p. 757-773.

Nelson, Craig J. and Riesmeyer, Duncan W. 1983, Geology of the Anaconda-Gunnison mine area, Gunnison County, Colorado, *in* Gunnison gold belt and Powderhorn carbonatite field trip, Guidebook, p. 8-18.

Olson, J.C. and Hedlund, D.C., 1973, Geologic map of the Gateview Quadrangle, Gunnison County, Colorado, United States Geological Survey Map GQ-1071.

Olson, Jerry C., Marvin, Richard F., Parker, Raymond L., and Mehnert, Harald H., 1977, Age and Tectonic Setting of Lower Paleozoic Alkalic and Mafic Rocks, carbonatites, and Thorium Veins in South-Central Colorado, Journal Research U.S. Geological Survey, v. 5, no. 6, 1977, p. 673-687.

Pearce, Julian A., Harris, Nigel B. W. and Tindle, Andrew G., 1984, Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks, Journal of Petrology, v. 25, p. 956-983.

Pearce, J.A., 1996, A User's Guide to Basalt Discrimination Diagrams, *in* Wyman, D.A, ed., Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration, Geological Association of Canada Short Course Notes, no. 12, p. 79–113.

Romberger, S.B., 1980, Metallic Mineral Resources of Colorado, *in* Kent, Harry, and Proter, Karen, eds., Colorado Geology, Denver, Colorado, Rocky Mountain Association of Geologists 1980 Symposium, p. 225-236.

Siegel, Frederic R., 1974, Applied Geochemistry, New York, New York, John Wiley and Sons, p. 353.

Sims, Paul and Stein, Holly J., 2003, Tectonic evolution of the Proterozoic Colorado province, southern Rocky Mountains; a summary and appraisal, Rocky Mountain Geology, v. 38, no. 2, p. 183-204.

Smith, David, B., 1995, U.S. Geological Survey Certificate of Analysis Syenite STM-1, http://minerals.cr.usgs.gov/geo_chem_stand/syenitestm1.html.

Sorensen, Henning, 1974, The Alkaline Rocks, New York, New York, John Wiley and Sons, p. 622.

Sun, S. and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle compositions and processes, *in* Saunder, A. D., and Norry, M. J., eds., Magmatism in the Ocean Basins, Geology Society Special Publication, no. 42, p. 313-345.

Taylor, Stuart Ross and McLennan, Scott M., 1985, The Continental Crust: its Composition and Evolution, Oxford, England, Blackwell Scientific Publications, p. 312.

Tweto, Ogden, 1980a, Tectonic History of Colorado, *in* Kent, Harry and Porter, Karen eds., Colorado Geology, Denver, Colorado, Rocky Mountain Association of Geologists 1980 Symposium, p. 5-9.

Tweto, Ogden, 1980b, Precambrian Geology of Colorado, *in* Kent, Harry and Porter, Karen eds., Colorado Geology, Denver, Colorado, Rocky Mountain Association of Geologists 1980 Symposium, p. 37-45.

Tweto, Ogden, 1980c. Summary of the Laramide Orogeny in Colorado, *in* Kent, Harry and Porter, Karen eds., Colorado Geology, Denver, Colorado, Rocky Mountain Association of Geologists 1980 Symposium, p 129-134.

Tweto, Ogden 1987, Rock Units of the Precambrian Basement in Colorado, United States Geological Survey Professional Paper 1321-A. Washington, D.C., p. 1-54.

USGS, 1982a, Gateview Quadrangle, Colorado-Gunnison Co., 7 ½ minute series (topographic), Denver, Colorado, U.S. Geological Survey.

USGS, 1982b, Powderhorn Quadrangle, Colorado, 7 ½ minute series (topographic), Denver, Colorado, U.S. Geological Survey.

Van Schmus, W., Bickford, Marion E., Anderson, J., Bender, E., Anderson, R., Bauer, Paul, Rotertson, James, Bowring, Samuel, Condie, Kent, Denison, Rodger, Gilbert, M., Grambling, Jeffrey, Mawer, Christopher, Shearer, C., Hinze, William, Karlstrom, Karl, Kisvarsanyi, E., Lidiak, Edward, Reed, John, Sims, Paul, Tweto, Ogden, Silver, Leon, Treves, Samuel, Williams, Michael, and Wooden Joseph, 1993, Transcontinental Proterozoic provinces. *in* Reed, John Jr., Bickford, Marion R., Houston, Paul Link, Rankin, Paul Sims, and Van Schmus, W., eds., Precambrian: Conterminous U.S., Boulder, Colorado, Geological Society of America, p. 171-334.

Warner, L.A., 1980, The Colorado Lineament, *in* Kent, Harry and Porter, Karen eds., Colorado Geology, Denver, Colorado, Rocky Mountain Association of Geologists 1980 Symposium, p.11-21.

Wilson, M., 1989, Igneous Petrogenesis, London, England, Unwin Hyman Ltd., p. 466.

Winchester, J. A. and Floyd, P. A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements, Chem. Geol., v. 20, p. 325-343.